Treball de Fi de Màster

Màster Universitari en Enginyeria de l'Energia (MUEE)

Analysis of the Costs, Variability and Evolution of Solar Photovoltaic Generation Projects for the Analysis by Learning-by-doing

Master Thesis

Autor: Bernat Abadal Bosch
Director: Lucas Van Wunnik

Convocatòria: Setembre 2019

ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

UPC

Summary

In this paper it will be evaluated and analysed the costs that compose a Solar PV project: modules, inverters and BOS (including the procedure and administrative management, taxes, sales effort, etc.) with the purpose to justify its big reduction and detect the responsible factors for such evolution: economy of scale, technology improvements, etc. Gathering most recent data for the registered prices, analysis of its evolution and future estimations by using the Learning-by-doing method. Also, it is compared such costs among the different countries, and it is also analysed its difference. Moreover, it is also studied the final price of the energy by means of the LCOE and the auction prices.

Index

1. Introduction

The scope of the project will be to study and analyse in detail the costs of Solar Photovoltaic projects for the different scale magnitudes and also compare them among most of the countries and regions in the world. For this matter, all the costs components associated in such projects will be considered, decomposed and studied separately, allowing this way to understand which are the fields in the Photovoltaics that account for a bigger share of the total share and also to detect which are more mature and which one are still to be developed.

Moreover, thanks to different databases on the small-scale projects from Australia, it will be possible to create the cost trend and evolution of the Solar Photovoltaic projects and, thanks to the tool of Learning-by-doing, it will be possible to predict the future prices for the small-scale projects.

2. Introduction: The fall of the prices of renewable energies and the outbreak of the solar energy

2.1. The evolutions of renewable energy and the reduction and uncertainty of their costs

Renewable energies have undergone an extraordinary market growth throughout the last 15 years, since generation costs have improved substantially and its deployment has been massively increased in terms of cumulative generation capacity, raising year after year. (Kost, Shammugam, Jülch, Nguyen, & Schlegl, 2018, pág. 8) (Maeda & Watts, 2019, págs. 540-541). Proof of that growth is the 419% net increase in renewable energy generation capacity (REN21). As shown in Figure 1, the total global cumulative renewable generation capacity (including hydropower) went from 1010 GW in 2007 to 2195 GW in 2017, according to the Global Status Report for each of the years, written by REN21. The inclusion of hydropower as a renewable source is a matter of debate since not all the installations are considered as renewable sources, e.g., Chile limits the power to 20 MW if hydropower installations wants to be considered as so. (Ley Nº20257, 2008). If it is excluded, the cumulative generation capacity drops to 240 GW in 2007 and 1081 GW in 2017, according to REN21.

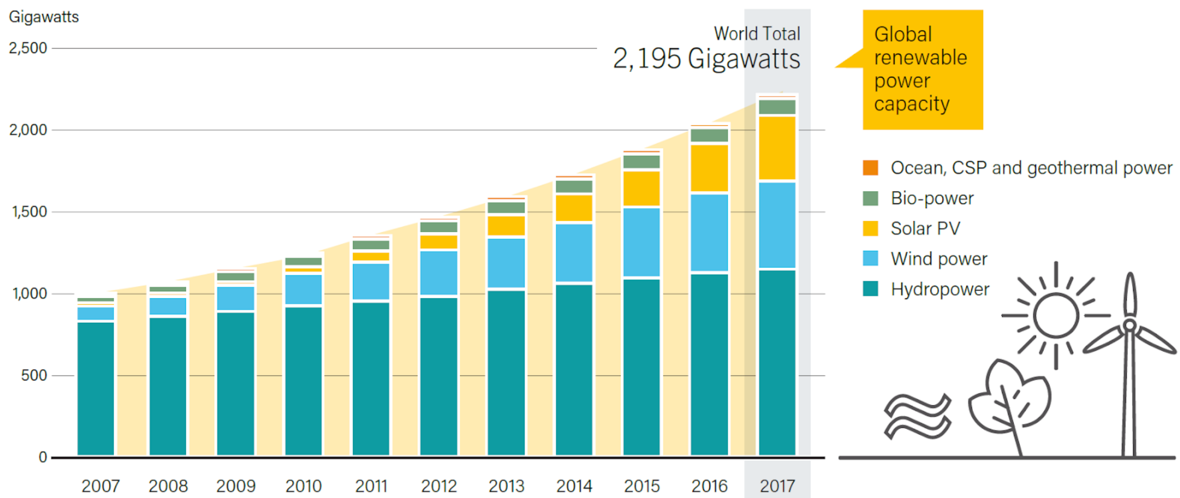


Figure 1. Evolution of the global renewable power capacity (considering hydropower) from 2007 to 2017. Reprinted from Renewables 2018. Global Status Report (pg. 41) by REN 21, 2019.

Among all the renewable technologies, and excluding hydropower (more mature), Wind Power and Solar Photovoltaics stand out as those with the most growth in the last decade.

However, the increase has been unalike, since the base point, back in 2007, was different. So, Wind Power, more implemented at that moment, went from 95 GW in 2007 to 591 GW in 2018 (accounting a 522% of growth), whereas Solar PV had just 8 GW in 2007 and increased to 505 GW in 2018 (6.212% growth).

Since 2016, Solar PV has experienced an enormous growth, led mostly by China and developing countries, surpassing Wind power in new generation capacity additions and placing as the first option for investors. The annual capacity additions evolution for the main renewable sources is shown in *Figure 2*, in there, there is proof of the fast and huge increase experienced by Solar PV (70% increase in 6 years) and the current difference with Wind power.

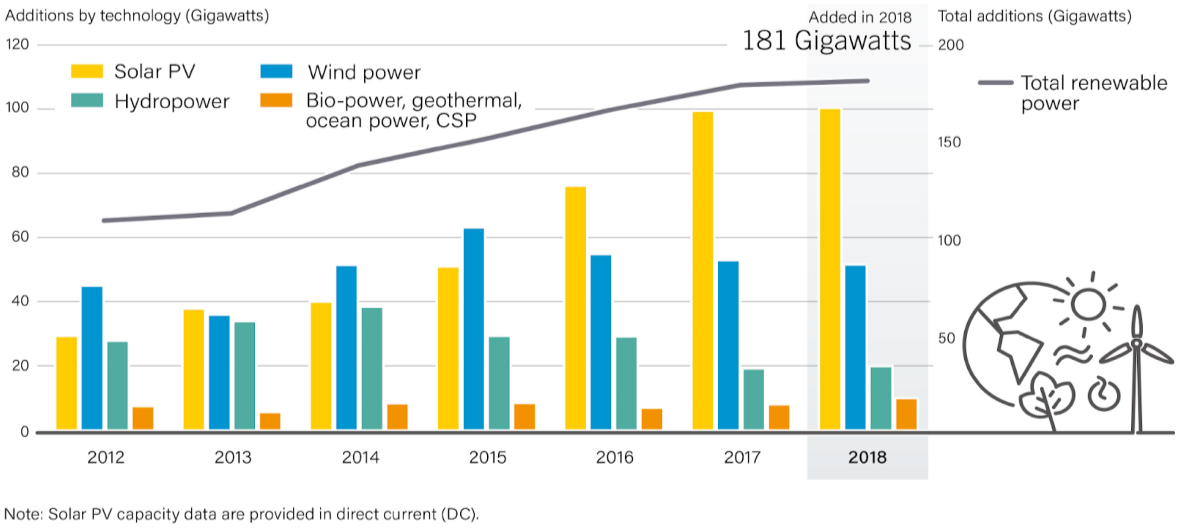


Figure 2. Annual additions of Renewable Capacity, by Technology and total, 2012-2018. Reprinted from REN21 Global status report 2019 (pg 40) by REN 21 Renewables Now, 2019. http://www.ren21.net/gsr-2019/

They might not expand at the same pace as how new capacity additions did, but investment in renewable energies have also played a key role on the growth of the market. This has been led by the reduction of the costs of renewable energies and the provision of support policies, making them more competitive with conventional sources. So, according to REN21 data in its global status report, the total investment in renewable energies has increased from $73 billion in 2005 to $280 billion in 2017 ($289 billion in 2018). As Figure 3 shows, there has been a diversion on the investment from developed countries to developing and emerging economies since 2015, “result of the lowering costs of renewable energy, rapidly rising demand for electricity in developing countries, the need for additional power generation capacity and changes in market regulations”, (Anh Nguyen, Abbot, & Nguyen, 2019, págs. 59-60) since e.g. China and India (Long, Cui, & Li, 2017) have introduced strong support policies for renewable energies, among others. During this period, 2017 was the year where the difference was the greatest.

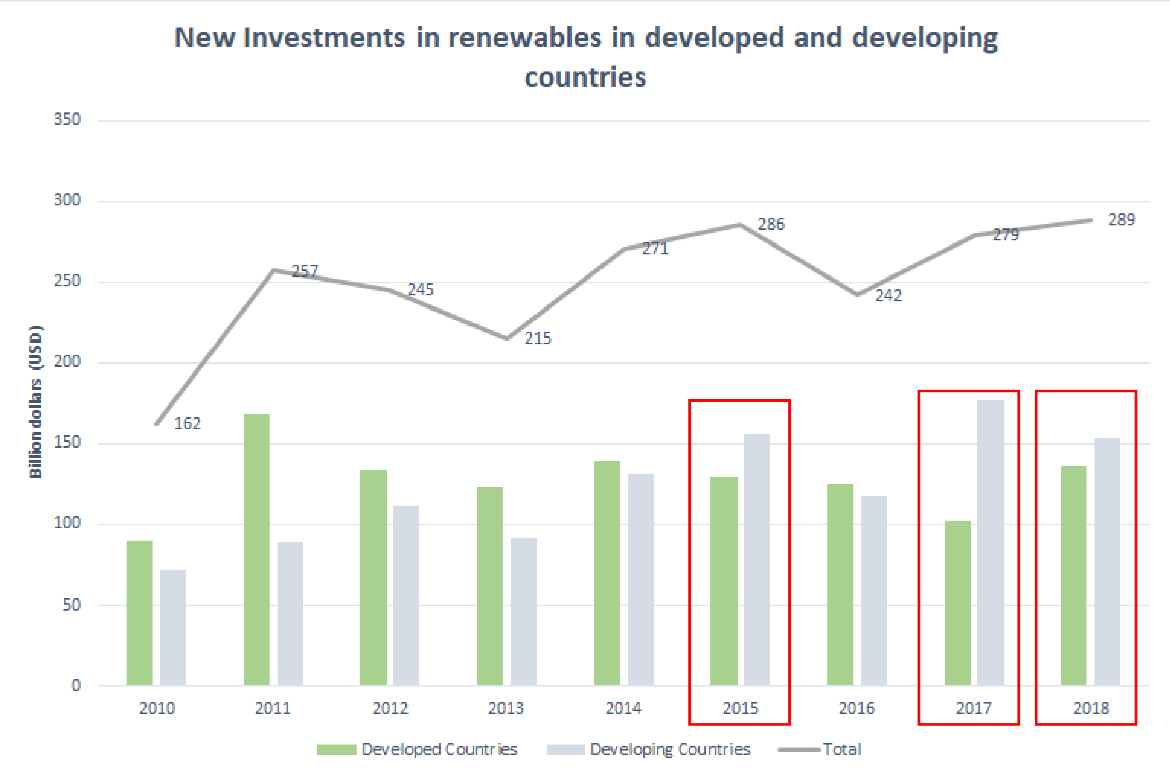
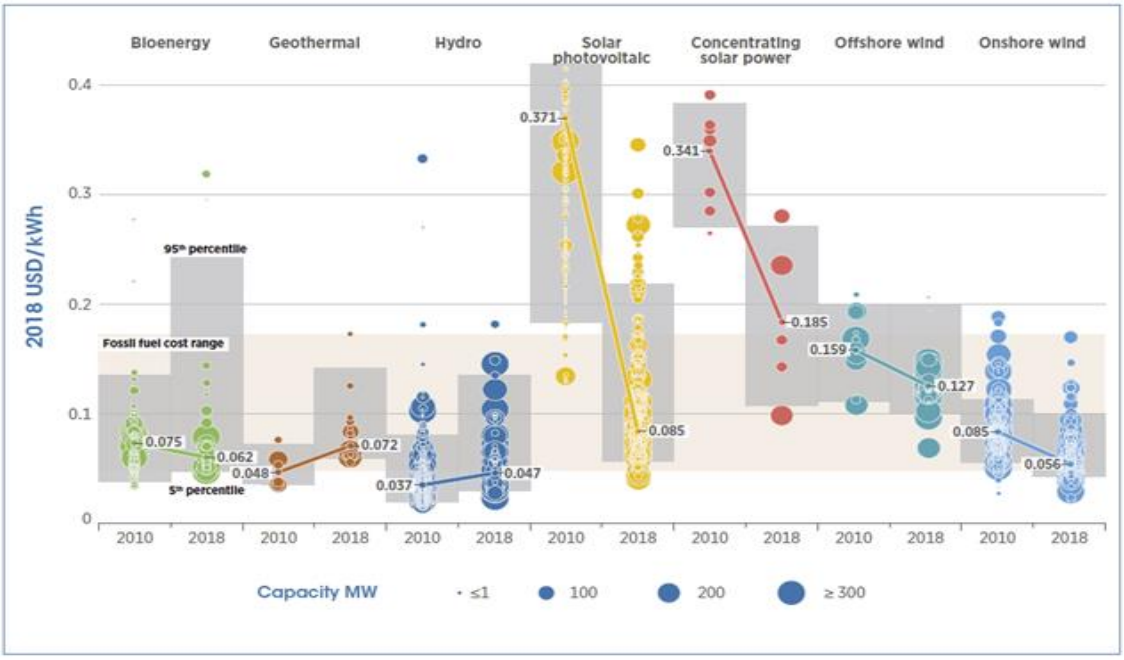


Figure 3. New Investments in renewable energies in developed and developing countries from 2010 to 2018. Source: Own creation using Renewable Energy Policy Network for the 21 Century (REN21), 2018b. Renewables 2018. Global Status Report. REN21, Paris. Retrieved from. http://www.ren21.net/statusof-renewables/global-status-report/

The market growth and the increase on the total new investments helped to "improve the system solutions with higher degrees of efficiency, lower production costs and lower operation costs" (Kost, Shammugam, Jülch, Nguyen, & Schlegl, 2018, pág. 8), leading to a LCOE reduction in all the renewable technologies, except of biogas power plants. (Kost, Shammugam, Jülch, Nguyen, & Schlegl, 2018, pág. 8)

An effect derived from the increase in the investments and the installed capacity is that, renewable energies -mainly wind, solar and CSP- are moving towards 'grid parity' with conventional sources both in price and performance (Motyka, Slaughter, & Amon, 2018, págs. 4-8) making it more preferred for the consumers (and prosumers) since it can also be an investment for the future becoming a source of income when injected to the grid. Understanding 'grid parity' as the LCOE comparison between renewable energies and "alternative means of wholesale electricity provision", although its definition still under debate within expertise community. (Bazilian, y otros, 2013). More precisely, IRENA states that these sources could be realistically competitive in the market by 2020. The constant reduction of their costs over the recent years have made this parity possible; in 2017 onshore **wind power** generation became the cheapest source of energy generation, with a LCOE between **USD$ 30 - 60 per MWh**, followed by the **photovoltaic solar generation** with a LCOE ratio of **USD$ 43 - 53 per MWh**, in a utility-scale perspective (Motyka, Slaughter, & Amon, 2018).

By looking at how close renewable technologies average LCOE values are from the minimum value of the fossil fuel cost range, is enough to look at *Figure 4*, to get a graphical justification on the idea that, indeed, renewable energy sources are getting closer to grid parity with conventional sources. In addition, all renewable has suffered a reduction (between 2010 and 2018) on the mean LCOE value, especially Solar PV, except for geothermal and hydropower that have increased their values within this period. Moreover, except Offshore wind and Concentrating solar power (CSP), the other renewable technologies account a LCOE average value lower than 0.1$/kWh (IRENA, 2019, pág. 12), making them, as said, very competitive.



Note: This data is for the year of commissioning. The diameter of the circle represents the size of the project, with its centre the value for the cost of each project on the Y axis. The thick lines are the global weighted-average LCOE value for plants commissioned in each year. Real weighted average cost of capital (WACC) is 7.5% for OECD countries and China and 10% for the rest of the world. The single band represents the fossil fuel-fired power generation cost range, while the bands for each technology and year represent the 5th and 95th percentile bands for renewable projects.

Figure 4. LCOE comparison and evolution within different energy sources in the utility-scale from 2010-2018. Reprinted from Renewable power generation costs 2018 (pg 12) by IRENA, 2019.

The worldwide LCOE evolution suffered by five renewable technologies since 2009 until 2017 is plotted in the *Figure 5.*

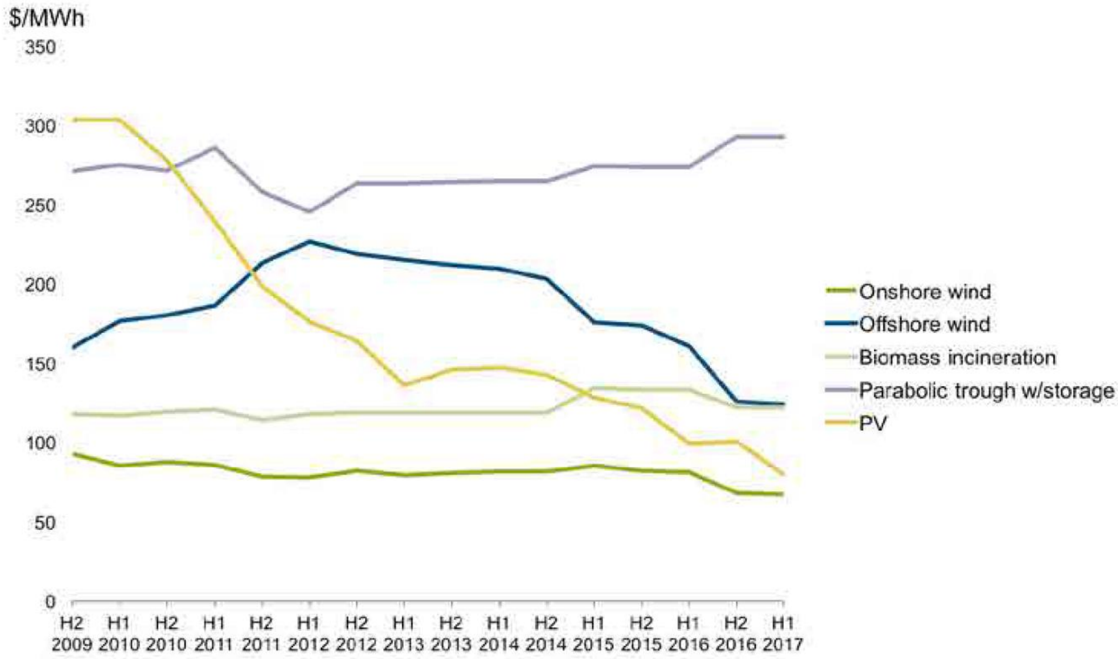


Figure 5. LCOE by Renewable Energy Technology 2009-2017. Reprinted from: Global trends in Renewable Energy Investment 2018. (pg 17). United Nations Environment and Bloomberg New Energy Finance - Frankfurt School, 2018

The reduction on the LCOE suffered by all the renewable technologies at a global level is remarkable, especially for Solar PV. Between 2009 and 2017 the LCOE for a Solar PV system without tracking systems fell from **$304/MWh** to **$86/MWh**, a 72% reduction. (Frankfurt School - UNEP Centre/BNEF, 2018, pág. 17) This has been, without a doubt, the most abrupt reduction among all the technologies.

The evolution from a set of technologies, conventional and renewables, of their mean LCOE in $/MWh in North America, a leading country in many of them, is plotted in *Figure 6*, demonstrating the decreasing trend on the energy costs. It is interesting to mention how steep was decreasing the price of the solar costs between 2009 and 2011, going from **359$/MWh** to **157$/MWh**. Actually all technologies besides Nuclear have suffered a remarkable LCOE reduction, but it is remarkable the role of Solar PV and Wind Energy, which have reached a cost level allowing them to compete in the market with gas energy with a current *LCOE* for the Solar PV in 2018 of **43$/MWh**, whereas for the case of Wind it was **42$/MWh,** a **69%** and **88%** reduction in this period. (LAZARD, 2018, pág. 7), shown in *Figure 6.*

Figure 6.Evolution of the Mean LCOE ($/MWh) for different energy sources in North America. Reprinted from Lazard's Levelized Cost of Energy v.12 (pg 7) by Lazard, 2018.

In fact, such decreasing evolution is more noticeable if a bigger time frame is taken, to where it used to be way more expensive. This data is gathered in *Figure 7* and it can be observed a huge price reduction for the renewable sources, especially for the Solar PV Residential.

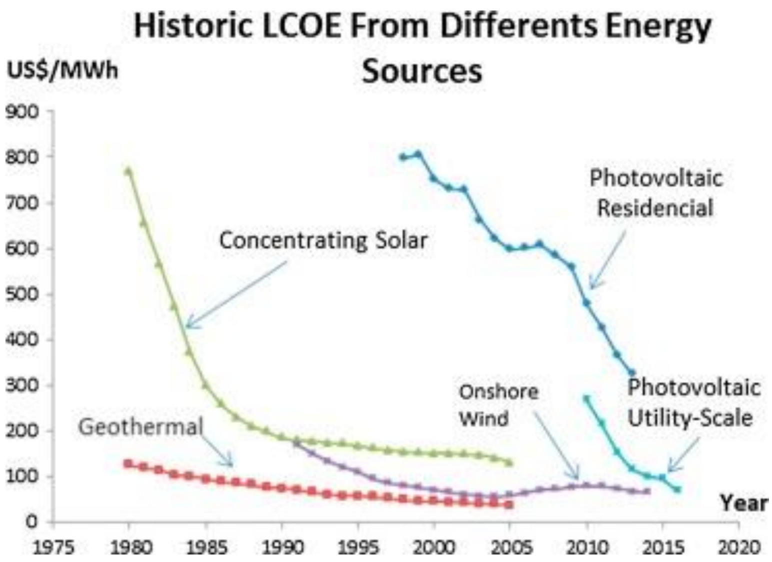


Figure 7. Historic LCOE from different energy sources. Reprinted from The unnoticed impact of long-term cost information on wind farms' economic value in the USA - A real option analysis (pg 541) by Mansaku Maeda and David Watts, 2019

One of the main drivers to this cost reduction is the fact that nowadays such renewable sources are no longer considered an obstacle for the grid in terms of intermittence. Quite the contrary, they are now able to be a solution for the grid balancing, becoming a source of resilience and reliability for the grid thanks to the introduction of smart inverters and advanced controls, allowing a faster ramp up than the conventional power plants and helping, this way, to stabilize the grid. Together with that, it is important to mention the improvement provided by the AI and machine learning in weather forecasting, which enables the optimization of the use of renewable resources, increasing the yields and performances of such type of power plants by selecting the best places for the exploitation of these sources.

Another key role that has recently emerged is the concept of Learning-by-doing, which benefited the industry sector by allowing a significant reduction of the production costs and helped to increase the quality of the products by acquiring experience, better organizing and sharing knowledge. (Tolouse School of Economics, 2018)

However, it has been proved historically that the increase on the capacity installed of a specific technology has a direct correlation with the price reduction. As it can be observed in *Figure 8* and *Figure 9*, the increase no the capacity installed in the US of Wind power and Solar PV technology, help its prices to decrease. This is the phenomena of the Learning-by-doing, which explains that as more installations and more mature is the technology, it gets improved and more efficient, making costs reduce, since a better knowledge and experience on the development and installation of systems is gained over the years.

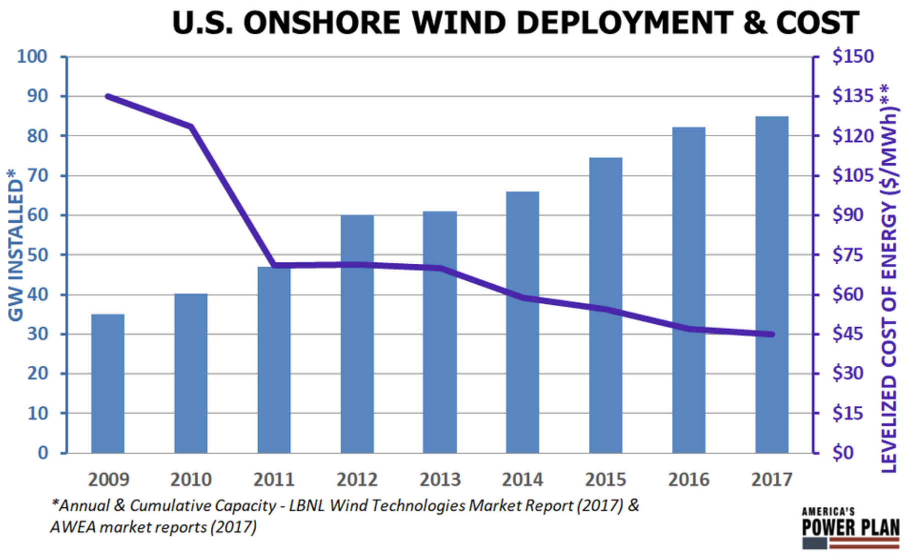


Figure 8. Annual and cumulative capacity Onshore Wind installed vs. LCOE from 2009-2017. Reprinted from Plunging Prices Mean Building New Renewable Energy Is Cheaper Than Running Existing Coal by Energy Innovation/America’s Power Plan, 2018

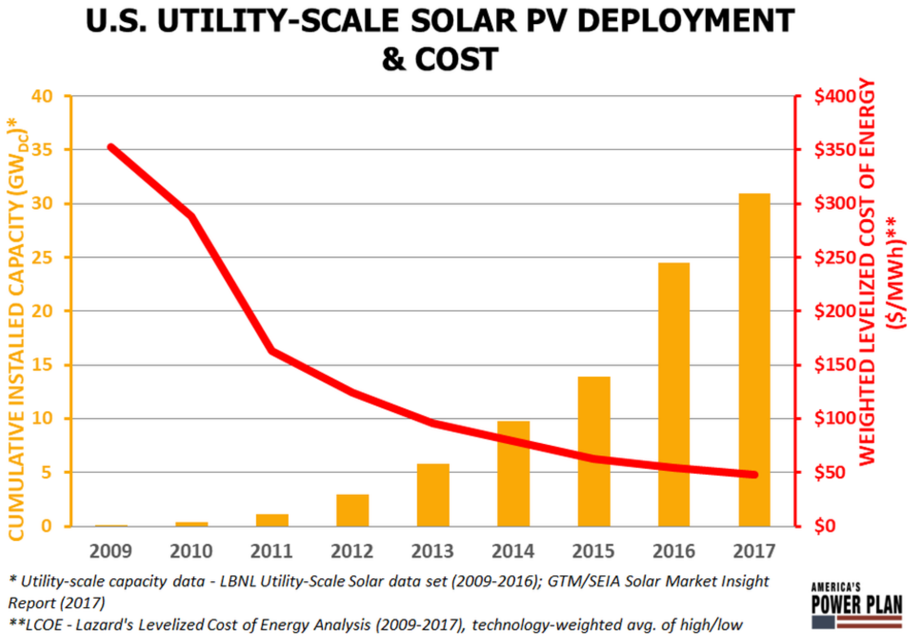


Figure 9. Annual and cumulative capacity Solar PV installed vs. LCOE from 2009-2017. Reprinted from Plunging Prices Mean Building New Renewable Energy Is Cheaper Than Running Existing Coal by Energy Innovation/America's Power Plan, 2018.

2.1.1. The debate: the appearance of tendering mechanisms brought better control and assurance for the government, but lower prices are paid for the technology in comparison with the levelized cost of energy (LCOE)

The Levelized Cost of Electricity (LCOE) has been designed as the best indicator to compare different technologies accounting different life spans, project size, capital cost, risk and return, since it considers all plant-level costs, e.g. initial investment, capacity factor, operational costs and fuel costs, due to its simplicity and easy-to-understand method and because it provides a better economic picture. (Dobrotkova, Surana, & Audinet, 2018, págs. 134-136) (Fatimah, 2019) (Bazilian, y otros, 2013). Moreover, it is used as a tool for policymakers to evaluate better the financial incentives to make renewable energies attractive for project developers or investors, e.g. (Bazilian, y otros, 2013) (Wassbein, Glemarec, Bayraktar, & Schmidt, 2013) and, also, for project developers or investors, who use it to analyze the economic viability of their projects or estimate the revenues requirements. (International Energy Agency (IEA) ; Nuclear Energy Agency (NEA), 2015) (Dobrotkova, Surana, & Audinet, 2018)

Nevertheless, the use of LCOE has its drawback since "it only measures generation costs within the perimeter of an individual plant and it does not consider the overall transformation costs that integrate variable Renewable Energies into the over-arching electricity system" (Fatimah, 2019). These costs are accounted in the integration costs *(additional cost of* *accommodating wind and solar into the power system by comprising variability and uncertainty costs)* (Fatimah, 2019) and system costs (total costs to generate electricity at a given level of load and availability of supply), which in part explores the dynamic effects of the variable Renewable energies such as the volatility of electricity prices in wholesale markets or the load factor reduction of dispatchable power generators. (Fatimah, 2019) Another constraint in LCOE is that the variability in renewable generation cannot be captured and it is sensitive to other assumptions changes. (Dobrotkova, Surana, & Audinet, 2018)

An alternative to LCOE are bid prices (usually given in $/kWh) since they not only involve the main LCOE parameters but also others such as market and currency conditions, benefits, incentives, auction guarantees and design, potential future earnings, etc. (Dobrotkova, Surana, & Audinet, 2018) By using it, more externalities are taken into consideration.

On the belief that it will help reduce costs, thus, increase its penetration on the energy mix and the aim of receiving more benefits for each renewable energy dollar (Elliott, 2018), (Fowlie, 2017) many governments are switching recently from Feed-in-tariffs schemes, consisting in an administratively set price being paid by authorities for the electricity generated from renewable energies over a long-term period, into auction/tendering mechanisms with long-term power purchase agreements, where the investors and installers offer their lowest price to win market share. (Thiéry, 2019) In auctions, project developers state the price per unit of electricity that they consider the project will be economically viable to be realized. (Energypedia, 2016). With this new scope, governments have a better control on the deployment of renewables, reducing its costs, and at the same time they add more pressure on manufacturers to create a more competitive market and, therefore, drive down procurement costs, prevents overcompensation and increases transparency. (Thiéry, 2019) In the case of Solar PV, auctions help to de-risk PV investments in developing countries since they are no longer part from the project developer or investor and belong to the stakeholders, better prepared to address these risks. (Dobrotkova, Surana, & Audinet, 2018)

The main disadvantages of using these mechanisms are that: it excludes new and small players and benefits big companies, more prepared to propose low bid prices, which could lead to a constraint in the market, and in the long run, less competition; the existing risk that no suitable offer is submitted or companies 'underbidding' so then not all the profit is obtained and according to Hans-Josef Fell tenders slow the cost reduction of renewable energy technologies according to the learning curve (Fell, 2017) (Elliott, 2018) (Fowlie, 2017) (Energypedia, 2014) In addition, the use of this mechanisms can lead to aggressive low bids offers, since the competition in the market and the will to gain share from the companies is big. (Fowlie, 2017) IEA emphasizes that these aggressive strategies resulted in cancellations or contract negotiations delaying the deployment of the projects in India. (IEA, 2019)

South-America and Asia were the regions that push harder to introduce this scheme in their regulatory framework. For example, Chile started implementing it in 2006, being a forefather in this aspect. Chile organizes technology neutral auctions and bidders compete either for hourly supply blocks of energy or quarterly (3 months) blocks. This type of bids has enabled renewables to compete with fossil-fuel plants in calls for tenders. (Kruger, Eberhard, & Swartz, 2018) the average bid price was 32,5 2017 USD/MWh, and its lowest bid was registered to 21,5 USD/MWh (in Solar PV). (Kruger, Eberhard, & Swartz, 2018). In the recent EY report about Renewable Energy Country Attractiveness Ranking, Chile is on the 11th place. (EY, 2018). The evolution of the auction bid prices in Argentina, Brazil, Chile and Mexico, top-20 renewable energy attractive countries (EY, 2018), is shown in *Figure 10*. In there, is graphic how fast auction bid prices have fallen year after year, reaching bid prices levels close to 20$USD/MWh in Mexico and Chile, in 2017 bids.

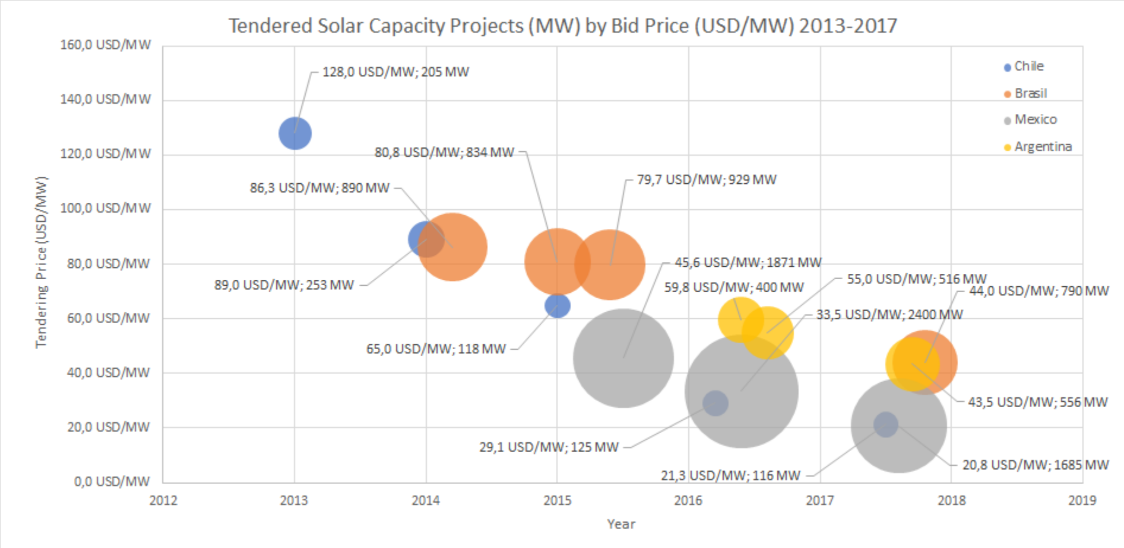


Figure 10. Tendered Solar Capacity Projects (MW) by their bid price (USD/MWh) for Mexico, Chile, Argentina and Brazil. Reprinted using data from Ecology Way. http://www.ecologyway.info/mexicos-record-solar-prices-fall-below-the-average-cost-of-energy-from-gas-and

To back the idea of how big the existing competitiveness in auctions is, *Figure 11* is shown. In there, the lowest bid prices in $US/MWh for Solar PV (left) and Onshore Wind (right) give proof that the lowest price are below 30 $US/MWh. Saudi Arabia (Solar PV) and Mexico (Onshore Wind) set a record on the prices offered, below 18$US/MWh.

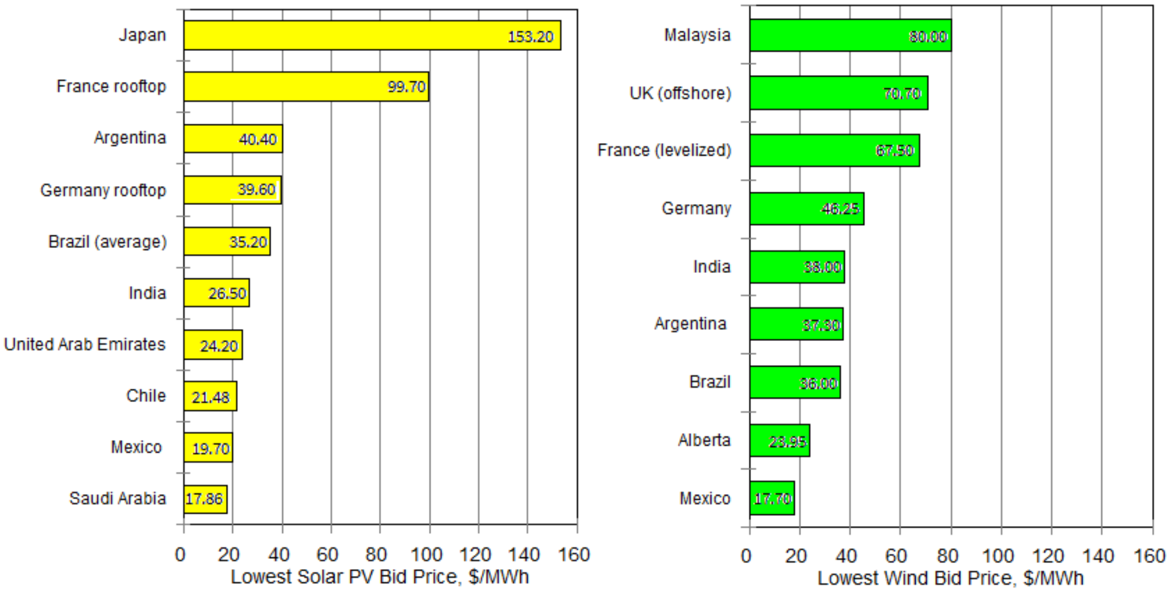


Figure 11. Low bid prices in $US/MWh for wind and solar in 2018. Reprinted from A review of recent solar and wind auction prices by Roger Andrews (Energy Matters). http://euanmearns.com/a-review-of-recent-solar-wind-auction-prices/

In conclusion, LCOE values tend to be higher than auction bid prices for different reasons: auction prices might not always consider full costs, the subsidies in countries like China and Japan making generation costs higher, the developers aggressive bidding strategies and the idea that auction prices just reflect a small part of the market. (IEA, 2019) To base this explanation, it is enough to look at *Figure 12*, where the evolution of LCOE and auction bid prices from Solar PV and Onshore Wind is plotted from 2010 and 2020. In this case, the values shown correspond to the average 5th percentile of the data gathered from *IRENA,* both for Solar PV and Onshore Wind, being the second, the one accounting the higher values. There is, then, a graphical proof that, indeed, average auction bid prices are lower than LCOE.

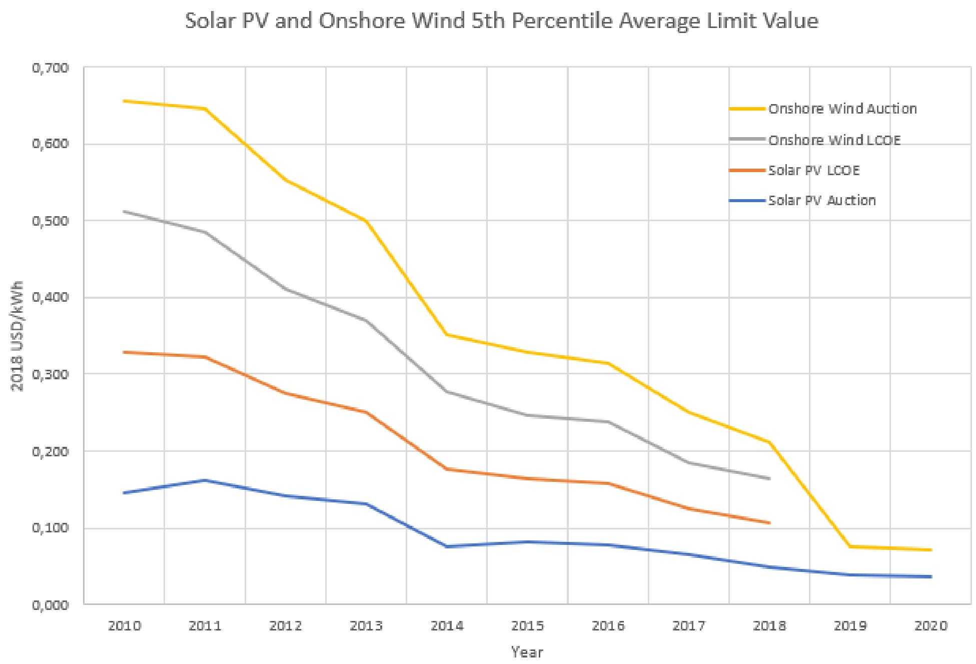


Figure 12. Solar PV and Onshore Wind 5th Percentile Average limit values in Auction bid prices and LCOE. Reprinted from data provided by IRENA Renewable Power generation costs in 2018.

2.1.2. The solar PV progress towards a leading position and the reduction of their costs at all scales

As it has been explained in previous section, the cost reduction in the Solar PV sector has been one of the most exceptional evolutions among all the renewable sources. Such evolution has been the result of all the advances in hardware and the maturity of the technology itself. In order to understand how has been driven such evolution is necessary to know all the components that compose a PV installation and how the costs regarding each of them has progressed to reach the current situation.

As it can be observed in *Figure 13*, a Solar PV installation is composed basically by 5 items:

1. PV modules
2. Inverters
3. Hardware BOS
4. Installation Labor Soft Costs

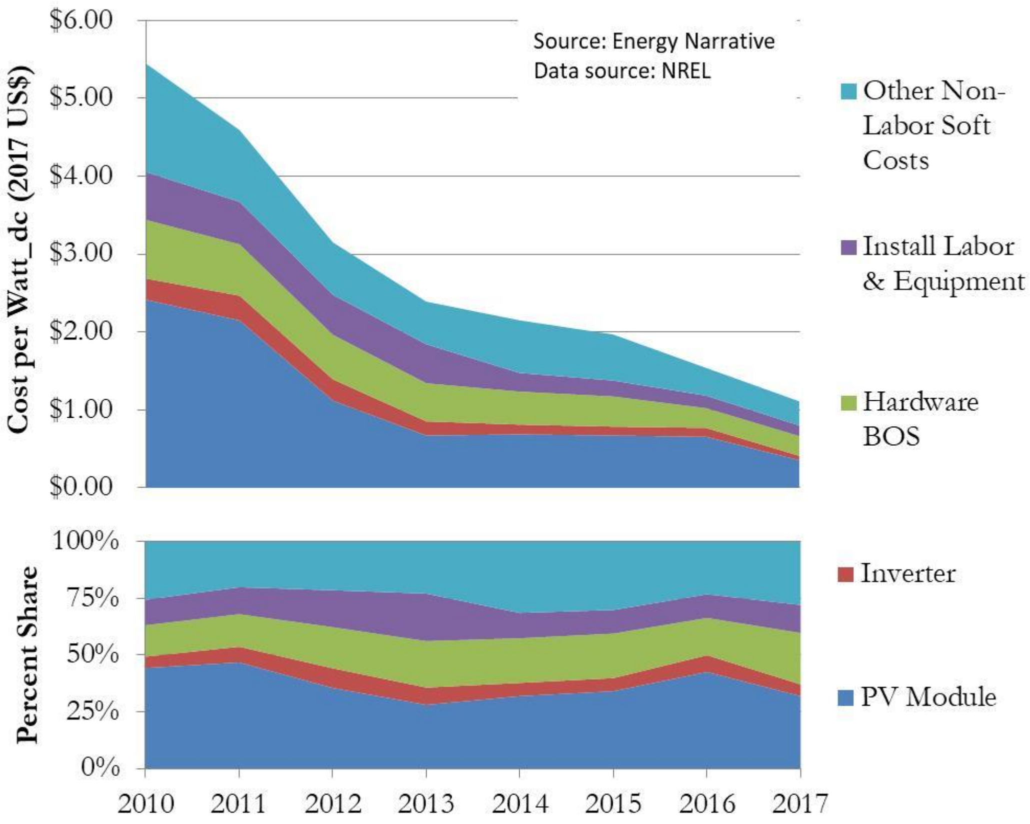
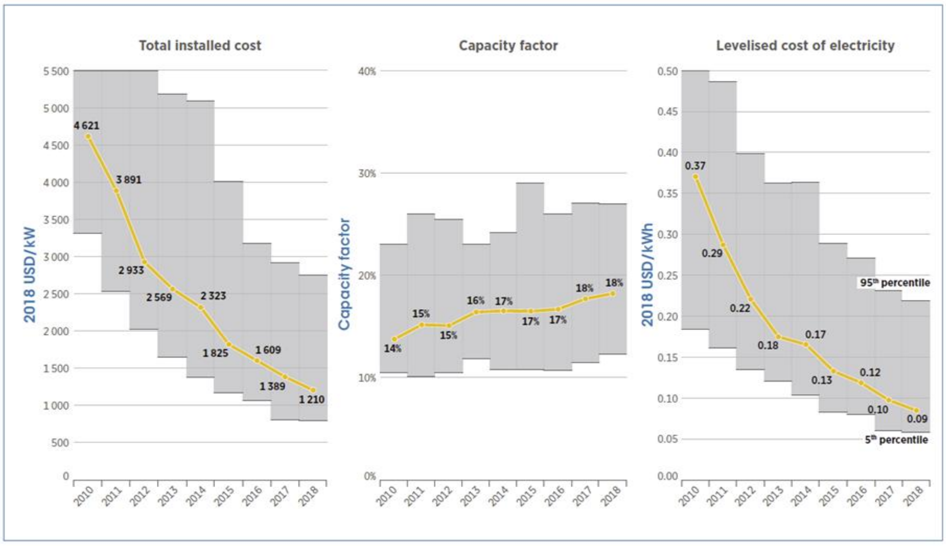


Figure 13. U.S. average utility-scale, single-axis tracker PV system costs by component, 2010-2017. Reprinted from Getting PV to 2 cents per kWh: Panel vs balance of system costs (https://energynarrative.com/getting-pv-to-2-cents-per-kwh-panel-balance-of-system-costs/) by Energy Narrative, 2018.

Observing *Figure 13*, all the components have experienced, in certain measure, a reduction in its cost, specially the PV modules, which are now reaching prices below the 0.02 $/W.

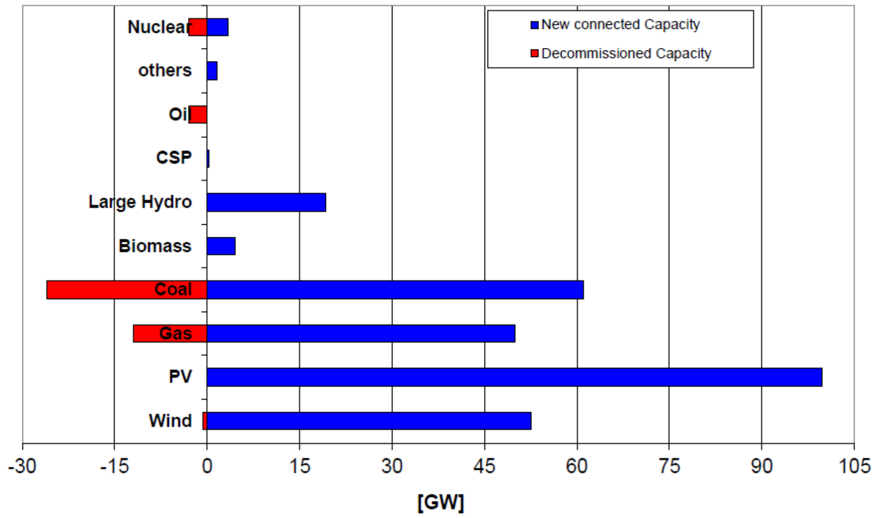
As it has been explained, the fact that such technology is gaining importance in the energy sector and more and more installations are being constructed, makes that technology more mature, enabling to find more efficient processes of manufacturing and installation resulting in a less costly technology which also means a cheaper electricity produced. This phenomenon is easily summarized in *Figure 14*, which shows how the total installed cost has been reduced considerably as the capacity factor has increased, leading to an impressive LCOE reduction.



Note: Solar PV, unlike all other technologies in this report have their costs expressed per kilowatt direct current (DC) and their capacity factors are expressed as an AC-to-DC value.

Figure 14. Global weighted average total installed costs, capacity factors and LCOE for solar PV, 2010-2018. Reprinted from Renewable Power Generation Costs in 2018 (pg 22) by IRENA, 2019.

The year 2017 was considered a true boom for Solar PV since its capacity was increased more than any other type of power generating technology. (REN21, 2018) During that year, around 99.8 GW of power were installed, which meant the 34% of new installed capacity, as the *Figure 15* demonstrates (Jäger-Waldau, 2018). As it is shown, PV new installations stands out in front of the rest renewable energies, worldwide.



Source: [FSU 2018, Gwe 2018, IEA 2018, Wna 2018] and own analysis

Figure 15. New connected or decommissioned electricity generation capacity world-wide in 2017. Reprinted from PV status report 2018 (pg 5) by European Commission, Jäger-Waldau, A., 2018.

In this sector China is accounted as the leading country in the Solar PV capacity and additions, just in 2017 they add nearly 53.1GW, ant they reached 131.1 GW installed in the country, as *Figure 16* indicates. It is then followed by United States, Japan, Germany and Italy. India appears on the third place when it comes to new capacity additions, since there is a strong government policy towards the installation of renewable sources.

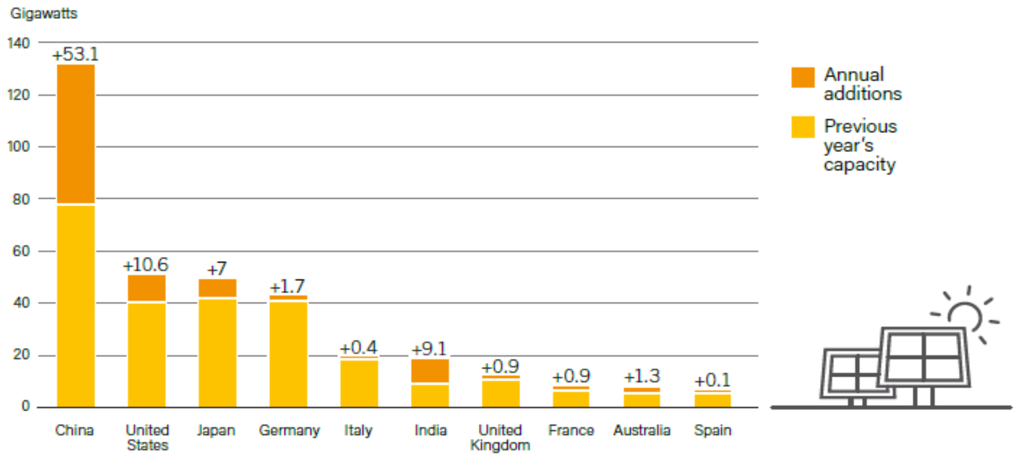


Figure 16. Solar PV Capacity and Additions for the TOP 10 countries in 2017. Reprinted from Renewables 2018 Global Status Report (chapter 3: Market and Industry Trends. Solar Photovoltaics, http://www.ren21.net/gsr-2018/chapters/chapter_03/chapter_03/) by REN21

The capacity of each country could be used as an indicator in order to understand how developed and mature this technology can be and, therefore, how low the prices can become in this precise location. Together with that, it is important to consider the investment that each of these countries is allocating to the Solar PV sector, which also affects the final prices, since it allows more investigation leading to new advances in technology and more efficient processes that can be also translated into cost reductions. In terms of investment, in 2017 *Solar Energy* accounted $161 billion, *Figure 17,* for new projects (58% of all new renewable energy investments), mainly in developing countries such as China ($126.6 billion) or India ($10.9 billion), although in the USA ($35.2 billion) and Japan ($13.4 billion) there were also big investments. On the other hand, in Europe the investment accounted to be $40.9 billion.

The global trend for the investment in the PV Solar technology is plotted below in *Figure 17*, as well as the cumulative installed capacity in both appear to be growing over time.

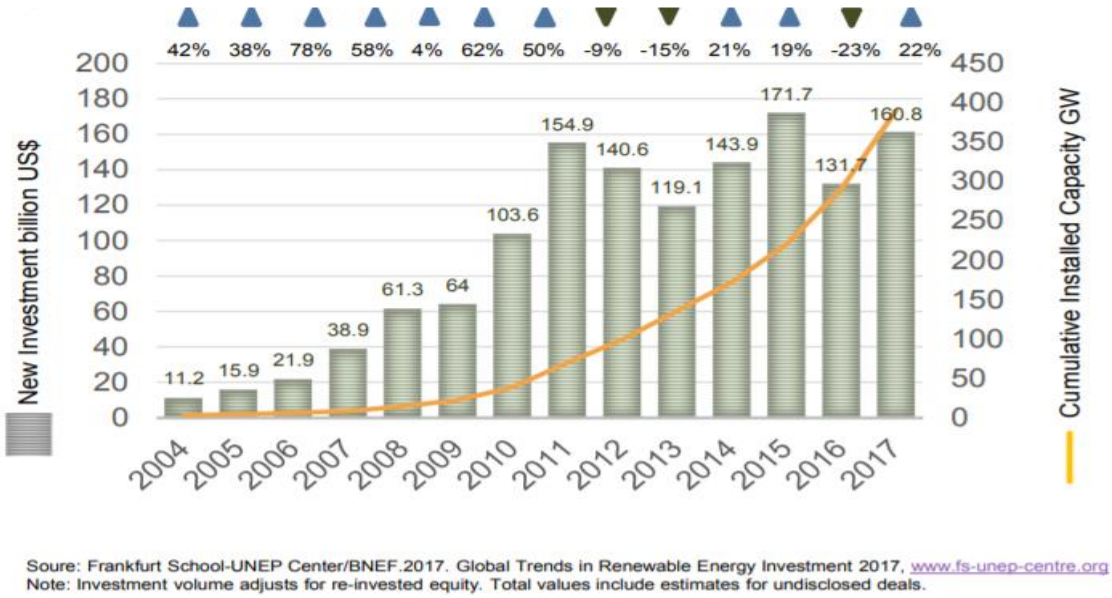


Figure 17. Global solar power investments vs. cumulative installed capacity. Reprinted from Solar PV technologies status and evolutions (pg 3) by Dr. Nabih Cherradi, 2018.

The effect of such increase in the installed capacity is proved in *Figure 18*, where it can be observed that the cost to install solar PV systems has dropped more than 70% over the last decade, allowing the industry to expand into new markets and deploy thousands of systems nationwide. Prices as of Q4 2018 are at their lowest levels in history across all market segments. An average-sized residential system has dropped from a pre-incentive price of $40,000 in 2010 to roughly $18,000 today, while recent utility-scale prices range from **$28/MWh - $45/MWh**, competitive with all other forms of generation.

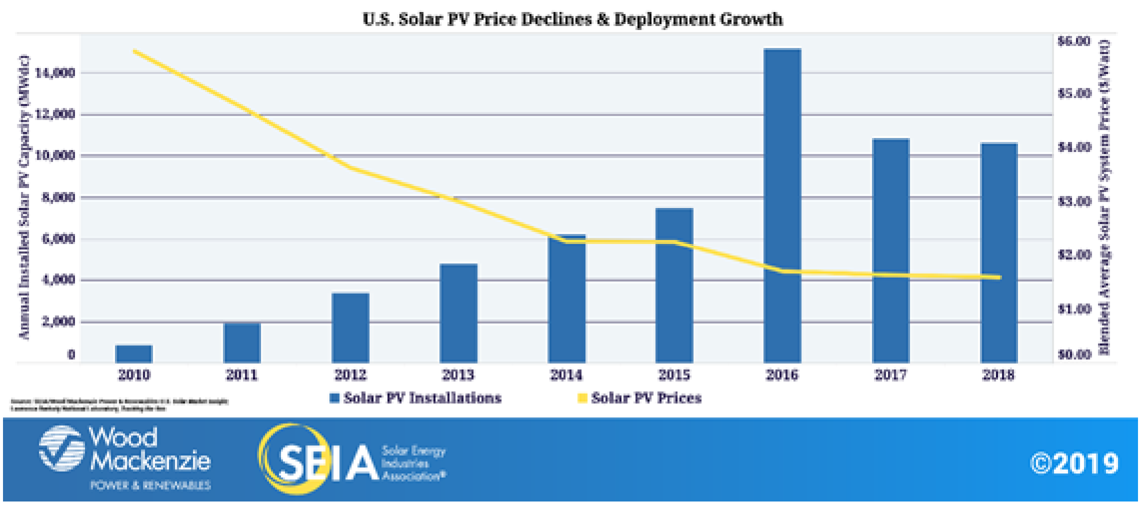
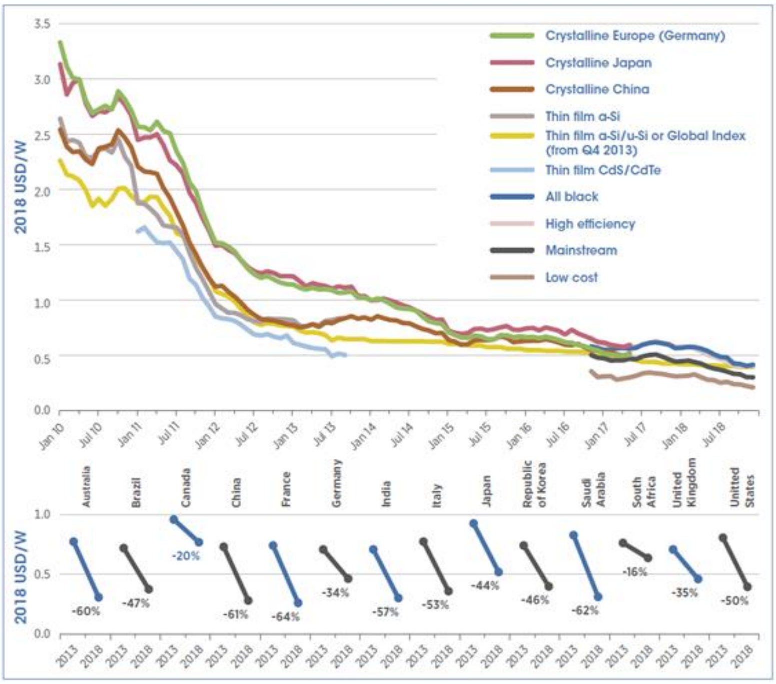


Figure 18. U.S. Solar PV Price Declines & Deployment Growth. Reprinted from Solar Industry Research Data (https://www.seia.org/solar-industry-research-data) by SEIA, 2019

2.2. Cost reduction trend of the solar modules: The most significant cost reduction of the PV technology

From all the different PV module technologies on the market, Crystalline silicon-based photovoltaics accounts to be the most used although Si-wafer based PV technology accounted for about 95% of the total production in 2017 (Fraunhofer ISE, 2019) Most of the global production of the modules (around 70%), are manufactured in Asia; being China, Taiwan and Japan its leaders. A key parameter that has helped on the rapid growth of the PV market has been the efficiency of the panels, that has increased 5% during the last decade (IRENA, 2018, pág. 59). However, and as it is highlighted in the uncertainty on the data gathered and presented regarding solar cell production is important, since the way companies show its numbers differs. (Jäger-Waldau, 2018) For that reason, values might vary within the reports online.

It is not necessary to set a big-time frame to analyze how fast and steep has been the cost decrease trend regarding the solar modules. For example, according to the *Renewable Power Generation Costs in 2018 (IRENA)* report, in the period 2010-2018 the cost of the solar modules was reduced over 83% in *Europe.* This reduction is shown in *Figure 19*, where the price evolution on this period for different solar panel technologies manufactured in distinct regions of the world is plotted. It demonstrates that the trend is quite similar for the whole set of different solar modules technologies, the reduction has been constant throughout the period, being less steep in the latest stages rather than the first ones, when it decreased greatly.



Sources: Based on GlobalData, 2018; IRENA Renewable Cost Database, 2019; Photon Consulting, 2018; and pvXchange, 2019.

Figure 19. Average monthly European solar PV module prices by module technology and manufacturer, Jan 2010 - Jul 2018, from Power Costs 2018 Report (pg 43) by IRENA, 2019.

In the *IRENA Power Costs 2018 Report* (IRENA, 2019) it is outlined that further reductions in the module costs will be related to improvements in the production processes and to efficiency gains associated with increased adoption of newer cells designs.

According to the (Fraunhofer ISE, 2019), there are at least 4 types of technologies to produce PV modules. Three of them are already mature technologies: *Multi-crystalline Silicon*, *Mono-crystalline Silicon* and *Thin film technology*, whereas the other one is just a concept to be fully developed based on *Perovskite*. The evolution of the production of the mature technologies has suffered some changes; at the beginning of the century the mono-crystalline was the preferred option among the three. However, nowadays the multi-crystalline has raised to the top, accounting a 60.8% share on the production in 2017. Even though, mono-crystalline still has a 32.2% share, while thin film technology owns a 4.5% share. This evolution is plotted in *Figure 20.* It can be seen how *Silicon mono-crystalline* decreased its production share drastically since the late 90’s in favor of *Silicon multi-crystalline*.

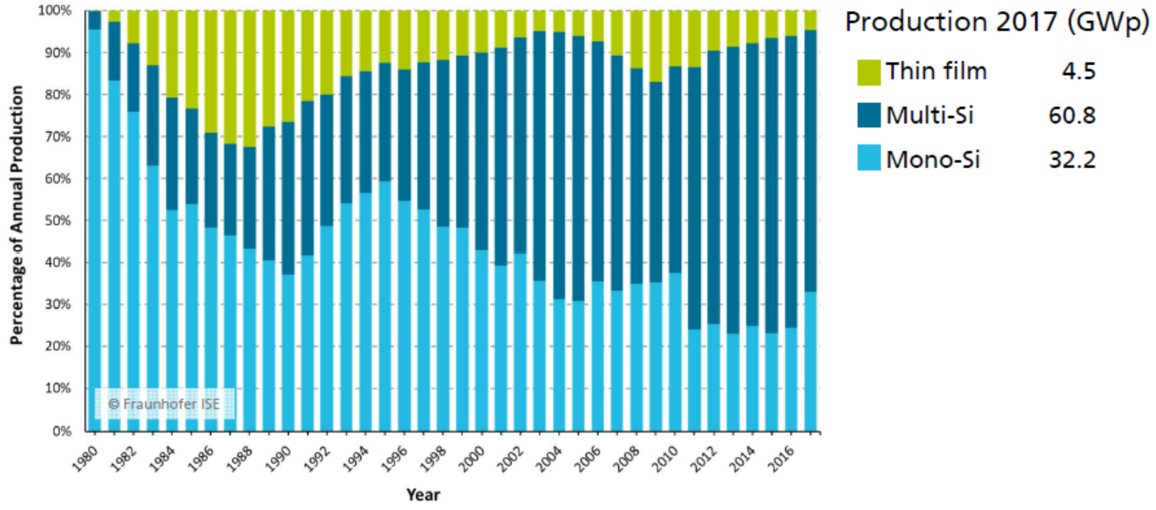


Figure 20. Percentage of Global Annual Production for each of the technologies, 1980-2017. Reprinted from Photovoltaics Report (pg 21) by Fraunhofer, 2019.

Although it has been arduous, some sources regarding current prices on the market have been found. They were mainly online websites, although others have been checked as *Wood Mackenzie* (SEIA, 2019). They work as a database and publish prices regarding polysilicon, wafers, cells, solar modules or inverters. So, websites such as (Energy Trend, 2019), (PVinsights, 2019), (ENF Solar, 2019) or (Bijli Bachao, 2019) *(India market)* have been used. Some examples are *Figure 21*, *Figure 22* or *Figure 23.* Depending on the website, the information is more specific. So, for example, *Figure 23* provides the country where it is manufactured, the type, its power range, its efficiency and the price, being the more complete within the consulted databases. On the other hand, *Figure 21* only shows the range of prices in China (high, average, low) for different solar module and its type.

Solar PV Module Weekly Spot Price					
Item	High	Low	Average	AvgChg	AvgChg %
Poly Solar Module	0.310	0.200	0.216	↑ 0.001	↑ 0.47%
Poly Module in China	0.240	0.200	0.213	↑ 0.003	↑ 1.43%
Poly High Eff / PERC Module	0.350	0.225	0.256	- 0	- 0%
Mono High Eff / PERC Module	0.400	0.240	0.276	- 0	- 0%
Mono High Eff / PERC Module in China	0.270	0.240	0.250	- 0	- 0%
ThinFilm Solar Module	0.330	0.230	0.250	- 0	- 0%

Figure 21. Solar PV Module Weekly Spot price. Reported from PVInsights (website), http://pvinsights.com/indexUS.php consulted 2019-06-05

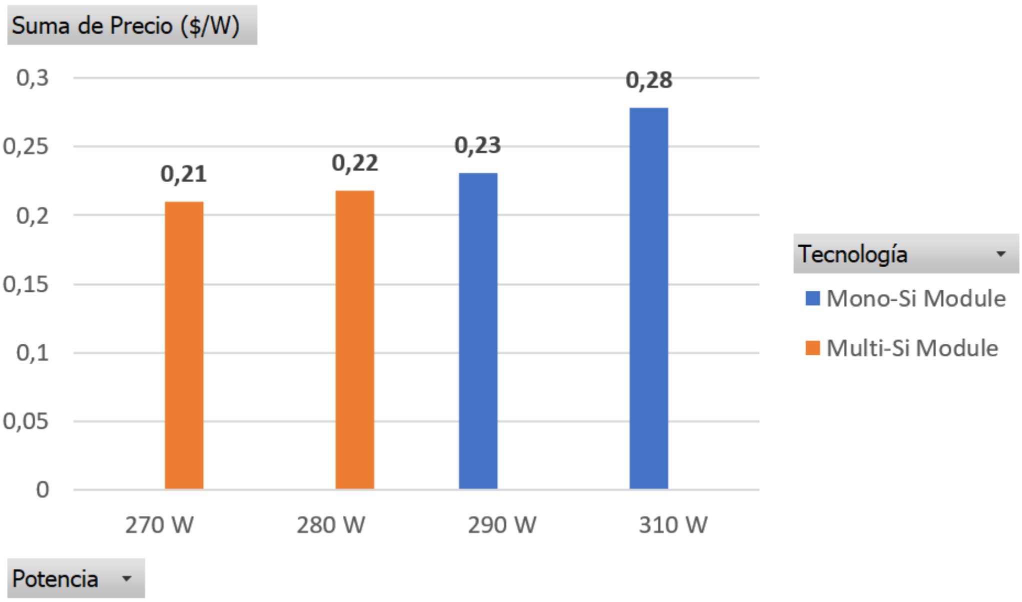


Figure 22. PV spot price for modules ($/Watt). Own creation using data published in Energy Trend (website). https://www.energytrend.com/solar-price.html, consulted in May 2019

Company Nam	Country	Series	Type	Power Range	Efficiency	Price Per Wp (€/Wp)
Hershey-Power	China	HS GLASS-GLA...	PERC	305 ~ 320 Wp	18.5 ~ 19.4 %	€0.285 / Wp
Luxen Solar Energy	China	LNSE-280-295...	Polycrystalline	280 ~ 295 Wp	16.85 ~ 17.75 %	€0.219 / Wp
Sunrise	China	SR-M660280-...	PERC	280 ~ 310 Wp	17.1 ~ 19.1 %	€0.245 / Wp
Sunpro Power	China	POLY 250W-28...	Polycrystalline	250 ~ 280 Wp	15.37 ~ 17.21 %	€0.205 / Wp
TPL Solar	China	TPL P-60 Ser...	Polycrystalline	255 ~ 280 Wp	15.67 ~ 17.1 %	€0.178 / Wp
Jiangsu Runda PV	China	RS280M6(B)-6...	Monocrystalline	270 ~ 290 Wp	16.6 ~ 17.8 %	€0.205 / Wp
Resun Solar	China	RS6S-P	Polycrystalline	300 ~ 325 Wp	17.12 ~ 18.55 %	€0.205 / Wp
Centro Energy	China	CE-295~320M6...	Monocrystalline	295 ~ 320 Wp	18 ~ 19.5 %	€0.214 / Wp
RaySolar	China	DM60-270-285	Monocrystalline	270 ~ 285 Wp	16.4 ~ 17.3 %	€0.330 / Wp
Just Solar	China	JST355-375M(...	Bifacial, PERC	355 ~ 375 Wp	18 ~ 19 %	€0.196 / Wp
GS PV	China	P6-300-340	Polycrystalline	300 ~ 340 Wp	--	€0.187 / Wp
Anhui Daheng Energy Te...	China	DHP72	Polycrystalline	315 ~ 330 Wp	16.25 ~ 17.02 %	€0.196 / Wp

Figure 23. Different features and Price per Wp (€/Wp) of various manufacturers from China. Reported from ENF Solar (website) (https://www.enfsolar.com/directory/panel) consulted July 2019.

Although it has already been mentioned, from the previous figures fast information can be extracted: China is the top country reaching lower prices. They already reached the 0.20 USD/Wp barrier for polycrystalline solar modules (money change at 11th July 2019: 1 euro = 0.8878 USD). However, some German manufacturers have reached 0.22 USD/Wp (ENF Solar, 2019), which means that they are on the hunt to get there too.

In *Figure 24*, a compilation of the data shown in *Figure 23* is presented. In there, the cost (USD/Wp) of monocrystalline (blue) and polycrystalline (brown) solar modules is exhibit just for the Chinese manufacturers. On it, the range of power that reaches 0.20 USD/Wp - 0.21 USD/Wp goes from 265 Wp to 340 Wp, making it a wide range. On the other hand, efficiencies are similar between the solar modules that reach that range of prices.

Figure 24. Set of solar module prices depending on its type of module (monocrystalline/polycrystalline), Peak Power Range (Wp), efficiency (%). Own creation using data from ENF Solar (https://www.enfsolar.com/directory/panel), 2019.

In the *U.S. Solar Photovoltaics System Cost Benchmark: Q1 2018* report from NREL (Fu, Feldman, & Margolis, 2018), *Figure 25,* it is shown the evolution of the multi-crystalline solar modules prices in the US market in comparison to the same type of module in a global perspective. The paths they followed from 2015 to the beginning of 2017 have similarities, since they were constantly reducing its price, although in the USA prices have always been more expensive. Everything changed since then, when the U.S. government approved a 30% tariff on imported solar modules. This tariff would decrease in the following years: 25% for the second year, 20% for the third and 15% for the fourth. This mechanism was implemented to allow domestic module manufacturers -without cell manufacturing capacity- to continue importing inexpensive cells, since a big part of them were being dismantled by the cheaper modules coming from China and South Korea. This tax only applies for imports above 2.5 GWp. (Delony, 2018) (BBC, 2018)

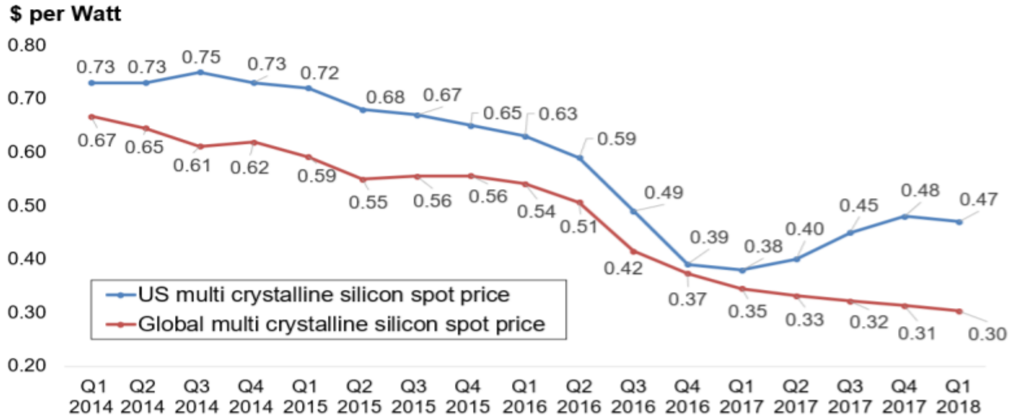


Figure 9. Ex-factory gate prices (spot prices) for U.S. and global multicrystalline-silicon modules from GTM/SEIA (2018) data

Figure 25. Ex-factory gate prices (spot prices) for US and global multicrystalline-silicon modules from GTM/SEIA (2018) data. Reprinted from U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (pg 12) by NREL, 2018.

A more recent study of the costs is carried in PV Magazine, Module Price Index (May 2019), where the cost evolution of the main technologies in EU is analyzed. As the *Figure 26* indicates, module prices for the most common technologies vary from 0.20 €/Wp for the low-cost technology to 0.35-0.36 €/Wp for the High efficiency and All black most advanced ones. (PV Magazine, 2019)

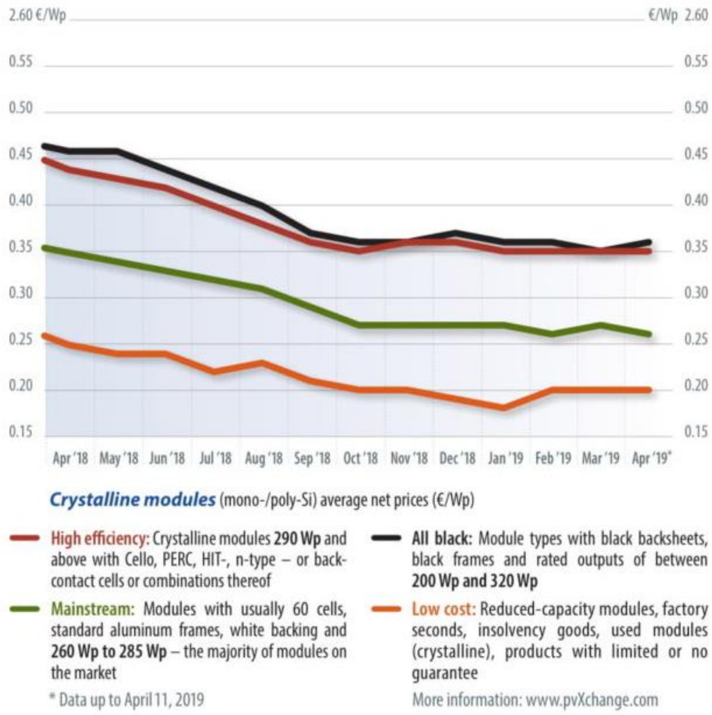


Figure 26. EU spot market module prices by technology. Reprinted from Module Price Index (https://www.pv-magazine.com/module-price-index/) by PV Magazine, 2019.

Following this trend analysis, it is shown in *Figure 27* the cost evolution of the PV modules per energy produced in the recent years in 3 indicative countries of this sector: Germany and the USA as leading countries in this technology with one of the lowest costs and Japan, which is known for having the more expensive modules prices. It is also remarkable the fact that the lowest prices of this technology are indicated for 2015, 2016 and 201, reaching costs of just a bit above the 0.02$/kWh. In *Figure 28,* the evolution trend since 1992 until 2017 is presented for the top-five manufactures in the world: Us, Japan, China, South-Korea and Germany.

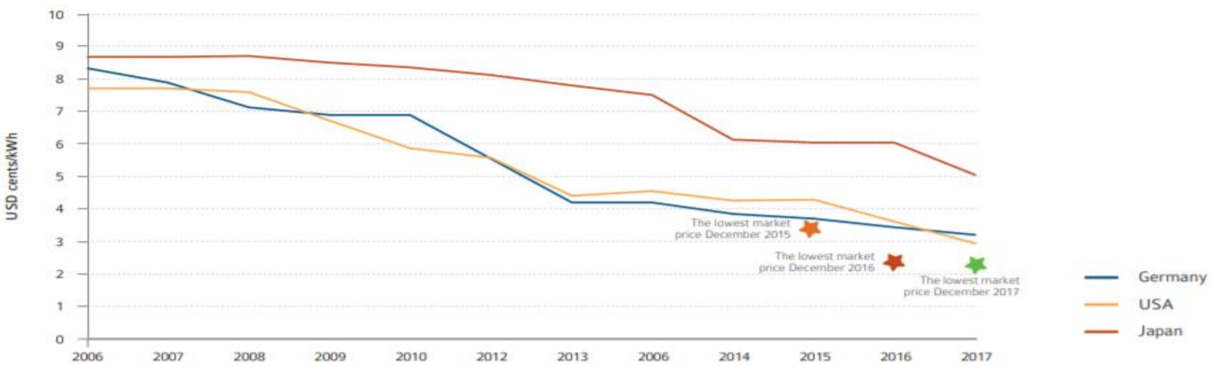


Figure 27. Evolution of PV modules prices in 3 indicative countries in USD Cents/kWh. Reprinted from Trends 2018 in photovoltaic applications (pg 71) by IEA, 2019.

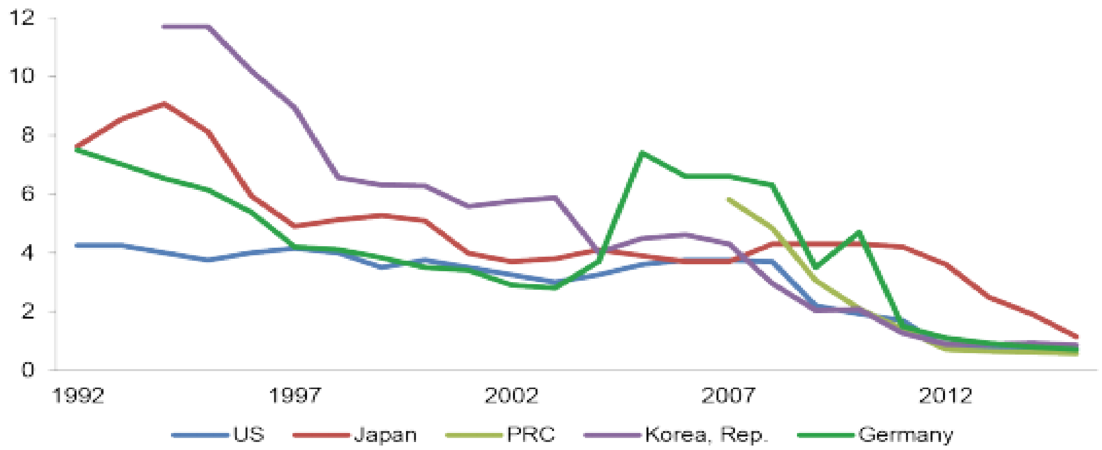


Figure 28. Price Change in Solar Modules for the Top Five Producing Countries from 1992 to 2015. Reprinted from Empirical Analysis of Factors Influencing the Price of Solar Modules (pg 3) by Farhad Taghizadeh-Hesary, Naoyuki Yoshino, and Yugo Inagaki, 2018.

2.2.1. The main drivers to solar modules costs reduction

In order to understand how such reductions in prices have been possible, a study was developed by Goksin Kavalak, James MacNerney and Jessika E. Trancik by means of an equation model it was investigated which of the “low-level” and “high-level” mechanisms were impacting the most the cost declination. (Kavlak, McNerney, & Trancik, 2018),

Considering a “low-level” mechanism each of the variables used in the model equation -in *Table 2*- and “high-level” the mechanisms which influenced those variables (research and development, learning-by-doing and economies of scale). There, by means of a cost decomposition strategy it was able to design an equation which would help to identify the most relevant factor that made the price reduce as much as it is shown in Table 1.

Table 1. Cost components in 1980, 2001 and 2012, in 2015 USD/W

Cost component	**1980**		**2001**		**2012**	
	$/W	**%**	**$/W**	**%**	**$/W**	**%**
Silicon cost	10.88	37%	0.55	13%	0.15	14%
Non-silicon cost	9.17	32%	1.21	30%	0.56	51%
Plant-size dependent cost	9.01	31%	2.33	57%	0.38	35%
Total module cost	29.07	100%	4.08	100%	1.08	100%

Note: Reprinted from Evaluating the causes of cost reduction in photovoltaics modules (pg 704) by G. Kavalak et al., 2018.

Even though that such costs are from 2012, it can be detected a huge price reduction in all these fields from the 1980 to 2012, especially in the Silicon cost. Then, thanks to the model described in (Kavlak, McNerney, & Trancik, 2018) it was able to determine the main drivers to such reduction.

Tabla 2. Contribution of the low-level mechanisms to module cost decline in 19080-2001, 2011-2012 and 1980-2012

Cost change due to	1980-2001		2001-2012		1980-2012	
	Δ$/W	**%**	**Δ$/W**	**%**	**Δ$/W**	**%**
Δ Efficiency	-5.96	24%	-0.35	12%	-6.30	23%
Δ Non-Si materials cost	-5.51	22%	-0.44	15%	-5.95	21%
Δ Silicon Price	-4.38	18%	-0.10	3%	-4.47	16%
Δ Silicon usage	-3.80	15%	-0.23	8%	-4.02	14%
Δ Wafer area	-2.71	11%	-0.48	16%	-3.19	11%
Δ Plant size	-2.07	8%	-1.08	36%	-3.15	11%
Δ Yield	-1.73	7%	-0.21	7%	-1.95	7%
ΔP_0	1.18	-5%	-0.12	4%	1.06	-4%
Change in module cost	29.07	100%	4.08	100%	1.08	100 %

Note: Reprinted from Evaluating the causes of cost reduction in photovoltaics modules (pg 706) by G. Kavalak et al., 2018.

As it is shown in *Table 2*, the most influencing "low-level" mechanism is the improvement of their efficiency, which has enabled modules to be more reliable in the market with a cost reduction influence of a 23%. Also has produced a high impact the improvement in the Non-Silicon materials, which includes the crucible used to produce silicon ingots; slurry and wire for the wire-sawing; aluminum and silver pastes, chemicals and screens for the cell manufacturing; and glass, frame, ribbon, back sheet, cable and junction box for the module. In *Figure 29,* it is graphically shown that contribution.

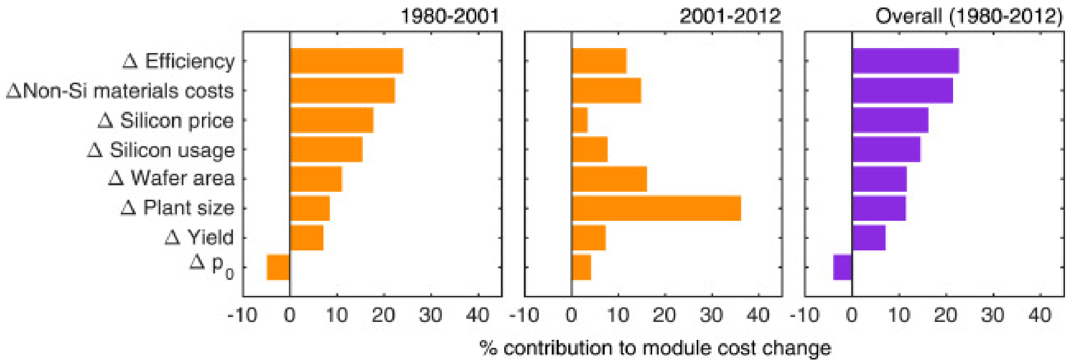


Figure 29. Contribution of the low-level mechanisms to module cost decline in 1980-2001, 2001-2012 and 1980-2012. Reprinted from Evaluating the causes of cost reduction in photovoltaics modules (pg 706) by G. Kavlak et al., 2018

In the *Photovoltaics Report*, March 2019, *Fraunhofer,* it is presented such a graph that includes the development of the solar cell efficiency, although the values shown are from laboratory samples, and how it has evolved. *Figure 30* gathers the data regarding the efficiency progression suffered by all known solar cell technologies during the last 25 years. As shown, all of them have experienced an increase on their values, although the pace has not been done in the same manner nor velocity. The trend can be observed that although Multi Crystalline Silicon that all types of cells has been experiencing a noticeable improvement in this area and more precisely the improvement experienced for the Crystalline-Silicon PV modules (*Figure 31*). (Fraunhofer ISE, 2019)

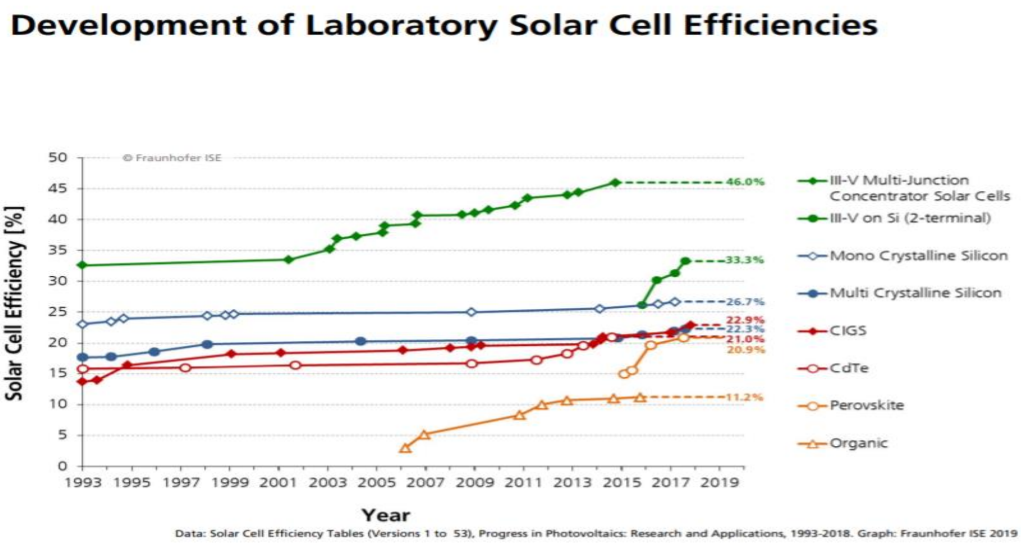


Figure 30. Development of Laboratory Solar Cell Efficiency. Reprinted from Photovoltaics Report (pg 27) by Fraunhofer, 2019.

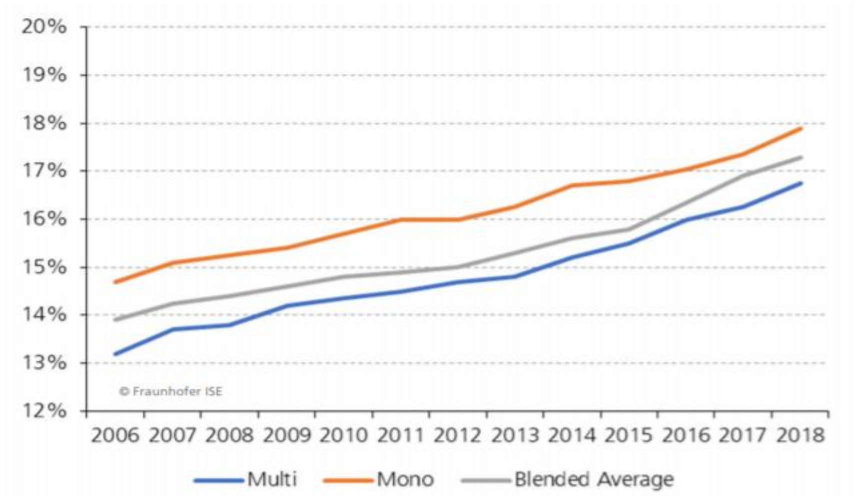


Figure 31. Average Crystalline-Silicon PV module efficiency performance 2006-2018. Reprinted from Photovoltaics Report (pg 28) by Fraunhofer, 2019

Moreover, Fraunhofer report also shows how the wafer thickness of the cells has decreased together with the reduction of usage of silicon in the Crystalline Silicon Cells, *Figure 32,* which also proves that this is a factor which has helped to reduce the costs regarding the PV modules. (Fraunhofer ISE, 2019)

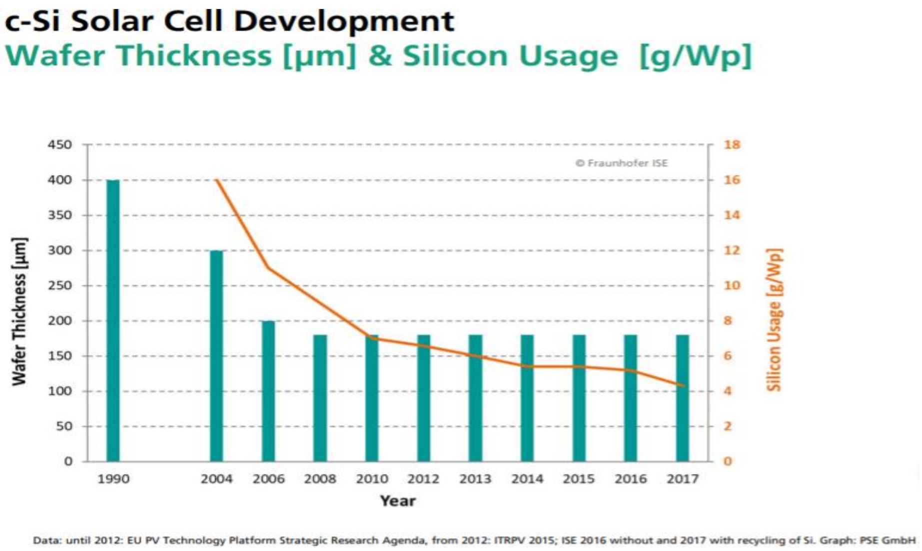


Figure 32. Wafer Thickness & Silicon Usage. Reprinted from Photovoltaics Report (pg 32) by Fraunhofer, 2019.

On the other hand, it is important to consider the "high-level" mechanisms, which are the reason of the "low-level" cost reductions -variables that directly affected the cost of technology-. These are mechanisms such research and development, learning-by-doing, and economies of scale, and its contribution in the module cost change is determined to be most influenced by the Public and private R&D (*Figure 33*). (Kavlak, McNerney, & Trancik, 2018)

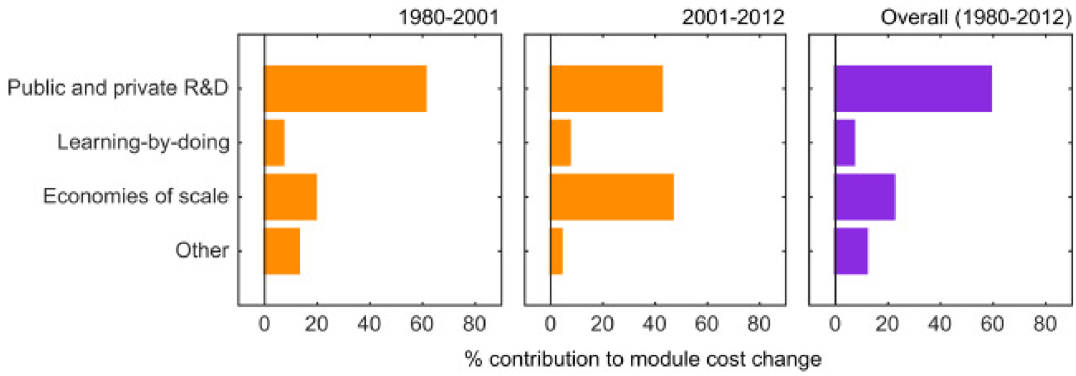


Figure 33. Contribution of the high-level mechanisms to module cost decline 1980-2012. Reprinted from Evaluating the causes of cost reduction in photovoltaic modules (pg 706) by G. Kavalak et al., 2018.

Related to these mechanisms, in (Kavlak, McNerney, & Trancik, 2018) the authors declare that even that low-level factors, like improvements in PV components and manufacturing processes, have had an important impact to the cost decreases, the main factor have been the high-level mechanisms as economies of scale and public policies.

2.3. The direct costs of the solar PV: Solar Panels and balance of System as the main drivers of the solar PV cost reduction

Besides the important advance in the technology of the PV modules and the impact on its costs, is also important to consider all the other components that compose a PV system and its cost evolution/trend: the so-called Balance of System (BOS) such as inverters and other electrical and structural components.

Thanks to data from 19 different countries provided by IRENA (IRENA, 2019) it is shown the cost share of each of the cost categories that compose a PV Solar installation: Module and inverter hardware, BOS hardware and installation and the Soft Costs, which are not considered a direct cost. As it can be observed in *Figure 34*, the solar panels and inverters account for a major share of the total costs with a 38%, meanwhile the BOS hardware and its installation account for a 36%. The rest, the soft costs, the 26%.

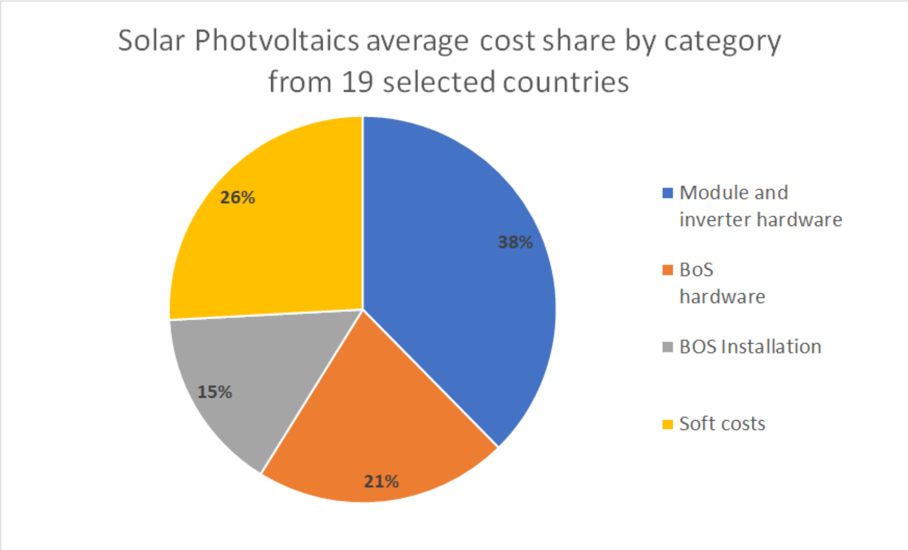


Figure 34. Solar Photovoltaics average cost share by category from 19 selected countries. Own creation based on data from IRENA, 2019.

Furthermore, thanks to NREL database (Fu, Feldman, & Margolis, 2018) it is possible to see the share of each of the categories for the different scale projects: residential, commercial and utility-scale. These average cost shares are referred to the costs for projects of 6,2 kW, 1 MW and 100 MW in the USA, which are the most representative cases of each of the scales described. Such comparison is shown in *Figure 35*, *36* and *37*, and it can be observed that the category that varies the most with the capacity change is the Soft Costs, which tend to decrease considerably for the big scale projects; it accounts for around 30% in the utility-scale projects meanwhile it arises to above 50% in the commercial and residential cases.

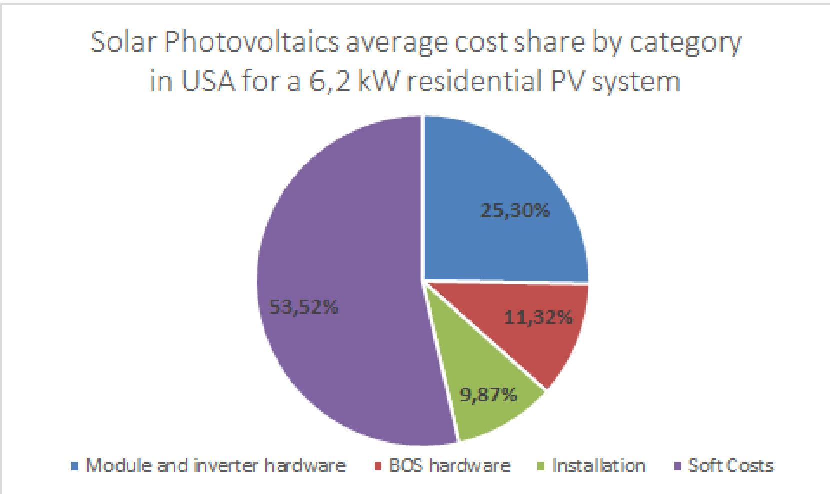


Figure 35. Solar Photovoltaics average cost share by category in USA for a 6,2kW residential PV system. Own creation based on NREL 2018 database.

ETSEIB

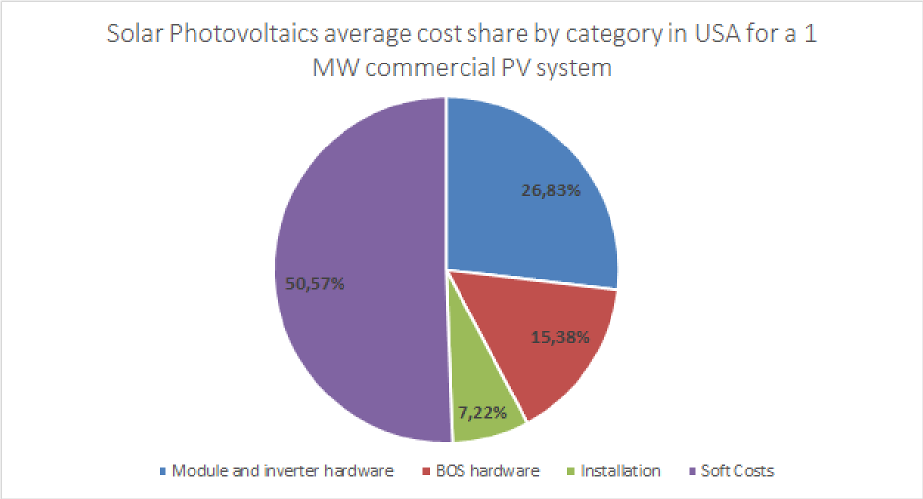


Figure 36. Solar Photovoltaics average cost share by category in USA for a 1 MW residential PV system. Own creation based on NREL 2018 database.

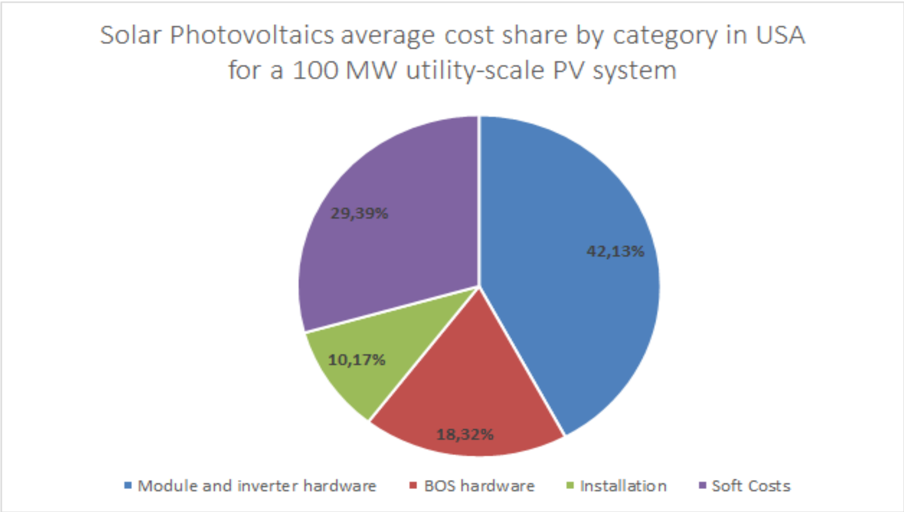


Figure 37. Solar Photovoltaics average cost share by category in USA for a 100 MW residential PV system. Own creation based on NREL 2018 database.

In this matter, NREL shows in his cost analysis report *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018* (Fu, Feldman, & Margolis, 2018), the costs of a PV system split into the different components: soft costs, structural and electrical balance of system and finally the module and inverter (*Figure 38*) in the sectors of residential PV, commercial PV and utility-scale.

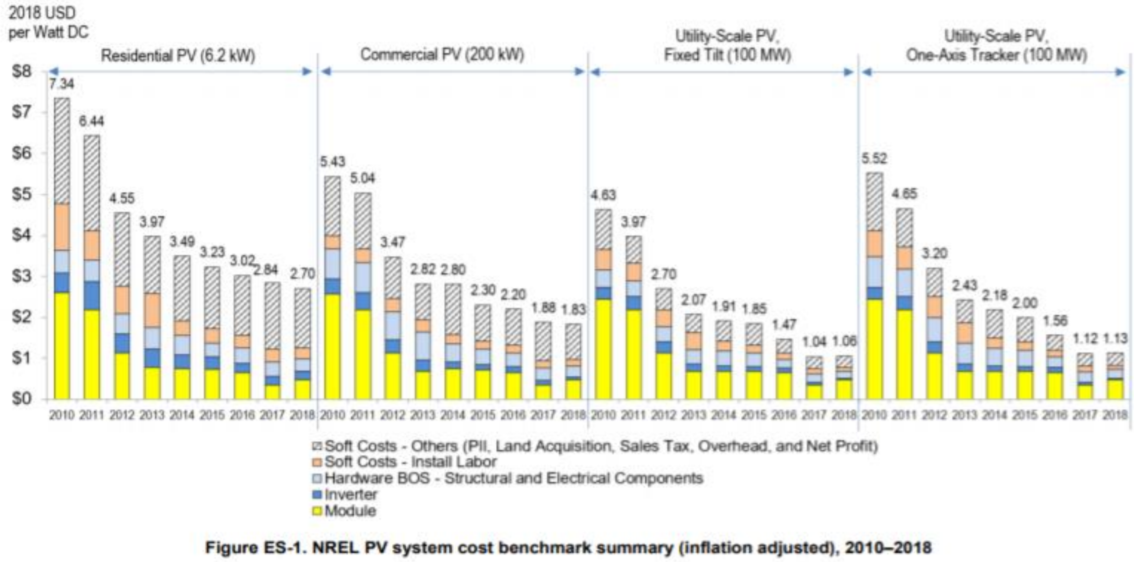


Figure 38. PV system cost benchmark evolution, 2010-2018. Reprinted from U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (pg VIII) by NREL, 2018.

In *Figure 38* it can be observed the global trend for the PV systems in the USA is to decrease, reaching prices close to 1 USD/Wdc in the utility-scale sector and a bit higher for those sectors of smaller magnitude. By checking the colors of the graphic, it can also be detected that such trend is led by the fact that module prices have been reduced considerably.

As for the BOS, it can also be said that they are being reduced but in a smoother way; however, it is somehow being more noticeable such reduction in the large PV systems than in case of the utility-scale sector or the commercial.

Furthermore, in the predictions made by Fraunhofer *Current and Future Cost of Photovoltaics, 2015*, (Fraunhfoer ISE, 2015) by means of some assumptions is predicted the total costs of an installation considering the BOS, inverter and module, compared to the price in 2014 (*Figure 39*), and it is expected to decrease up to a 36% in 2025 and even a 72% by 2050 in the best case scenario.

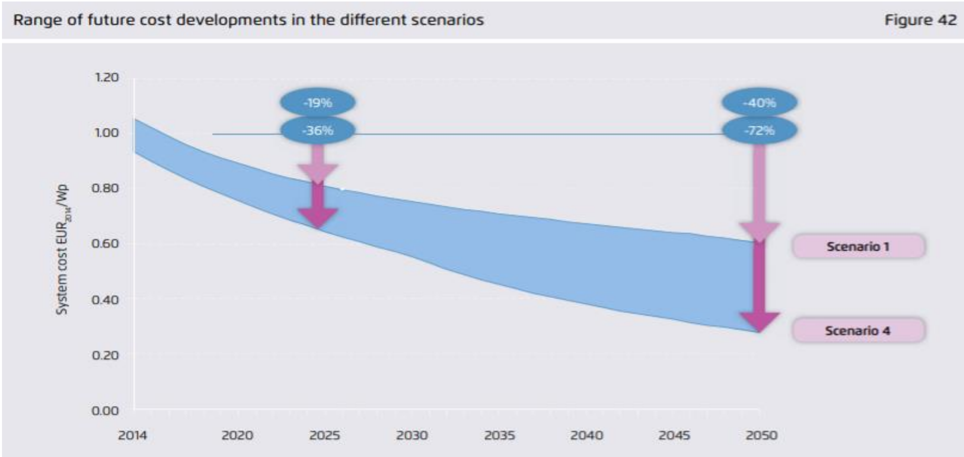


Figure 39. Range of future cost developments in different scenarios. Reprinted from Current and Costs of Photovoltaics (pg 52) by Fraunhofer, 2015.

This cost evolution is based on the assumptions made regarding each of the components that compute the total cost, including modules, inverters, and all the components inside the BOS: mounting system, installation, DC-cabling, infrastructure, transformer, grid connection and planning and documentation.

In more detail is possible to analyze each of these components that are present in a solar PV system thanks to *Table 3* and *4* from the *Solar Balance-of-System Costs Balance Cost Study*, by *Industrial Economics*, (Industial Economics, Incorporated (IEc), 2017) which exposes the system cost breakdown for a Residential and Commercial facilities in the U.S., based on the NREL data.

Table 3. Residential Cosgs, by Cost Component ($/Watt)

COST COMPONENT	NREL Q1 2016 BENCHMARK		NY BOS SURVEY AND MODEL		
	US AVERAGE	NEW YORK STATE	CON ED SERVICE TERRITORY	LONG ISLAND	REST OF STATE
Hardware and Materials Costs (Not Assessed or Modeled Separately from NREL Q1 2016)					
Module	$0.64	$0.64	$0.64	$0.64	$0.64
Inverter	$0.21	$0.21	$0.21	$0.21	$0.21
Structural BOS	$0.12	$0.12	$0.12	$0.12	$0.12
Electrical BOS	$0.25	$0.25	$0.25	$0.25	$0.25
Subtotal: Hardware and Materials	*$1.22*	*$1.22*	*$1.22*	*$1.22*	*$1.22*
Surveyed BOS Soft Cost Elements					
Permitting, Zoning, Inspection*	$0.10	$0.10	$0.24	$0.11	$0.11
Permit Fee*			$0.05	$0.05	$0.07 | $0.03
Interconnection* †			$0.05	$0.10	$0.25 | $0.23
Installation Labor	$0.30	$0.34	$0.39	$0.29 | $0.61	$0.29
Customer Acquisition**	$0.37	$0.40	$0.50	$0.48	$0.48
Subtotal: Surveyed BOS Soft Costs	*$0.77*	*$0.84*	*$1.23*	*$1.03 | $1.35*	*$1.20 | $1.14*
Other BOS Cost Elements (Modeled Based on NREL Q1 2016 Framework)					
Supply Chain/Logistics	$0.18	$0.20	$0.27	$0.19	$0.17
Sales Tax	$0.08	$0.05	$0.00	$0.00	$0.02
Overhead	$0.33	$0.36	$0.47	$0.34	$0.31
Profit	$0.35	$0.36	$0.42	$0.37 | $0.43	$0.40 | $0.39
Subtotal: Other BOS Cost Elements	*$0.95*	*$0.96*	*$1.16*	*$0.91 | $0.96*	*$0.90 | $0.89*
Total Cost	**$2.93**	**$3.02**	**$3.61**	**$3.15 | $3.53**	**$3.31 | $3.24**
Subtotal: Soft Costs	***$1.71***	***$1.80***	***$2.39***	***$1.93 | $2.31***	***$2.09 | $2.02***

Note: Reprinted from Solar Balance-of-System Costs Baseline Cost Study (pg ES-2) by Industrial Economics, Incorporated, 2017.

Table 4. Commercial Costs, Roof-Mounted Systems, by Cost Component ($/Watt).

COST COMPONENT	NREL Q1 2016 BENCHMARK		NY BOS SURVEY AND MODEL		
	US AVERAGE	NEW YORK STATE	CON ED SERVICE TERRITORY	LONG ISLAND	REST OF STATE
Hardware and Materials Costs (Not Assessed or Modeled Separately from NREL Q1 2016)					
Module	$0.64	$0.64	$0.64	$0.64	$0.64
Inverter	$0.13	$0.13	$0.13	$0.13	$0.13
Structural BOS	$0.17	$0.17	$0.17	$0.17	$0.17
Electrical BOS	$0.16	$0.16	$0.16	$0.16	$0.16
Subtotal: Hardware and Materials	*$1.10*	*$1.10*	*$1.10*	*$1.10*	*$1.10*
Surveyed BOS Soft Cost Elements					
Permitting, Zoning, and Inspection *	$0.05	$0.05	$0.06	$0.01 | $0.03	$0.06
Interconnection †			$0.02	$0.02 | $0.05	$0.50
Installation Labor	$0.19	$0.20	$0.42	$0.02 | $0.15	$0.21
Predevelopment / Origination** ††	$0.43	$0.41	$0.04 | $0.26	< $0.01 | $0.07	$0.43
Design & Engineering**			$0.03	< $0.01 | $0.03	$0.04
Subtotal: Surveyed BOS Soft Costs	*$0.67*	*$0.66*	*$0.57 | $0.79*	*$0.05 | $0.33*	*$1.24*
Other BOS Cost Elements (Modeled Based on NREL Q1 2016 Framework)					
Sales Tax	$0.07	$0.04	$0.04	$0.02	$0.03
Contingency	$0.06	$0.06	$0.07	$0.05 | $0.06	$0.08
EPC Overhead	$0.20	$0.19	$0.19	$0.19	$0.19
Profit	$0.04	$0.04	$0.04	$0.03	$0.05
Subtotal: Other BOS Cost Elements	*$0.38*	*$0.33*	*$0.34*	*$0.30 | $0.31*	*$0.36*
Total Cost	**$2.13**	**$2.07**	**$2.00 | $2.22**	**$1.44 | $1.73**	**$2.69**
Total Soft Costs	***$1.03***	***$0.99***	***$0.91 | $1.13***	***$0.35 | $0.64***	***$1.60***

Note: Reprinted from Solar Balance-of-System Costs Baseline Cost Study (pg ES-3) by Industrial Economics, Incorporated, 2017.

2.3.1. Solar panels: Accounting for the biggest share of the costs

Understanding a Solar Panel as a set of modules, it implies a different approach as for the cost's analysis. Additional to the costs of the modules and the absorptive material, when considering the solar panels, it has to be added the costs of manufacturing and also of those materials involved in the mechanical structure. In a recent study made by *Energy Sage*, an extended analysis on the solar panels costs was developed, just for the USA market, where it concluded an average national cost for solar panels of $3.05/Watt with an average solar system of approximately 6kW.

As Energy Sage shows in the graphic in *Figure 40*, the costs of the solar panels is also decreasing as the technology gets more mature and dropped up to a 21% their costs from 2014 to 2018, a trend that is likely to continue but in a smoother way in the following years.

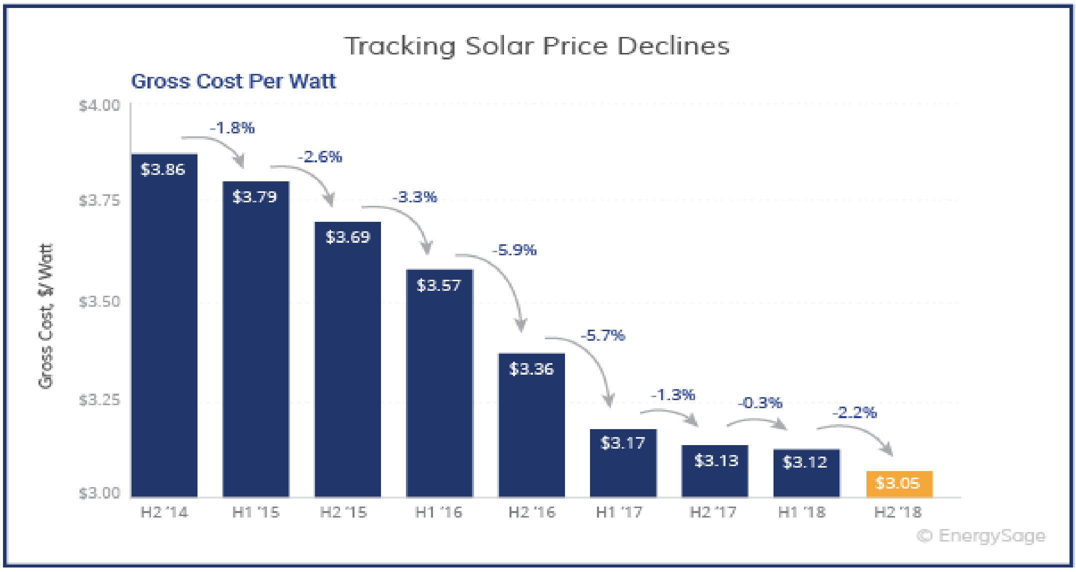


Figure 40. Tracking Solar Price 2014-2018. Reprinted from How much solar panels cost in the U.S. in 2019? (https://news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/) by Energy Sage, 2019.

The costs of the solar panels may vary depending on several factors besides the costs that come from the module technology; one of them is the country of the installation, which involves the incentives or subsidies at which the installation will be subjected. Also, the costs of the technology are also dependent on the manufacturers of that region, which, at the same time, could increase depending on the specific location due to the transportation and the equipment that might be required for the climate of that area and the type of building in which it has to be installed. However, the main driver to such costs is the size of the system to install, which is likely to decrease as the size of the system increases.

2.3.2. Inverters: the decrease on the prices and the appearance of the microinverters

Since inverters account for an important share of the total costs of a PV system, it is important to consider which is the trend or evolution of costs regarding this technology. Of course, there are multiple types of inverters, so it will be attempted to cover the cost of the most common inverters used in this field.

From the report from NREL 2018, *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018*, it is evaluated the inverter cost of each of the types used in the different sectors (residential, commercial or utility-scale), and convert its price from USD/Wac into USD/Wdc, as it is shown in *Table 5*.

Table 5. Inverter Price Conversion (2018 USD)

Inverter type	Sector	USD/Wac	DC-to-AC Ratio	USD/
Single-phase String Inverter	Residential PV (non-MLPE)	0.14	1.15	0.12
Microinverter	Residential PV (MLPE)	0.45	1.15	0.39
DC Power Optimizer String Inverter	Residential PV (MLPE)	0.20	1.15	0.18
Three-Phase String Inverter	Commercial PV (non-MLPE	0.09	1.15	0.08
Central Inverter	Utility-scale PV (fixed-tilt)	0.06	1.36 (oversized)	0.04
Central Inverter	Utility-scale PV (1-axis tracker)	0.06	1.30 (oversized)	0.05

Note: Reprinted from U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (pg 11) by NREL, 2018.

The trend experienced by the solar inverters is also notable, as it can be observed in *Figure 41*, prices decreased down below the 0.03 $/W in the first quarter of 2017, a trend that has been continuing until reaching prices even below the 0.02$/W.

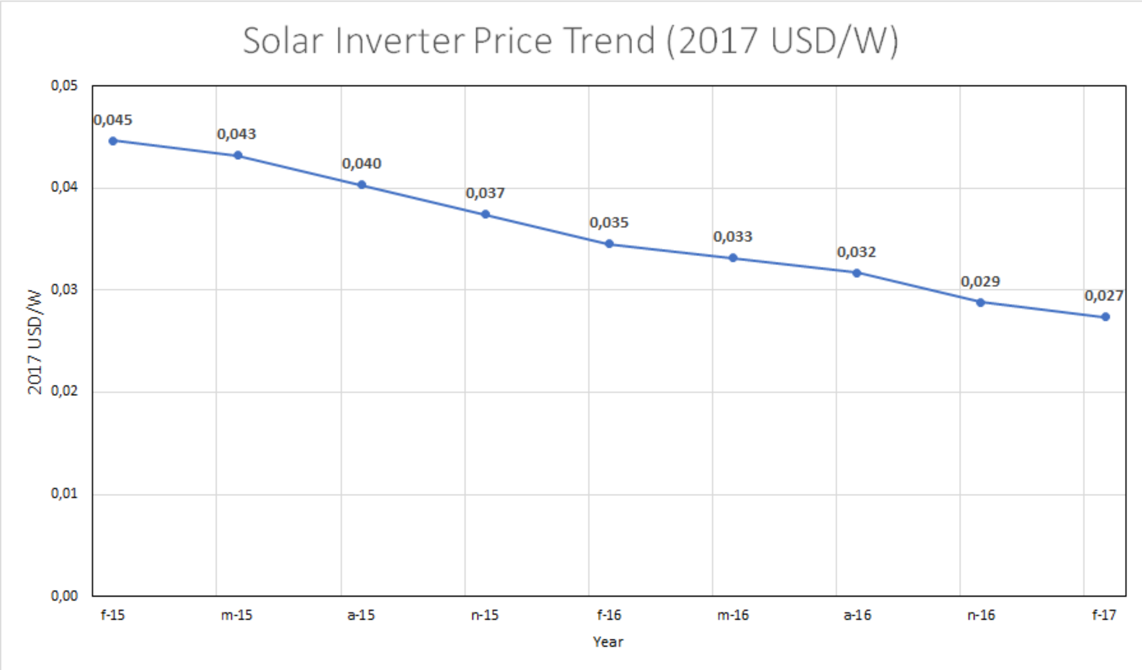


Figure 41. Solar Inverter Price Trend (2017 USD/W). Own creation based on data from Solar Inverter Trends (https://renewablewatch.in/2017/10/24/solar-inverter-trends/) by Renewable Watch, 2017. (1 Rs = 0,0144 USD, 23/06/2019).

2.3.3. Balance of System (BOS) costs

The Balance of System Costs, by definition, concerns all the components of a PV Solar System besides the Solar Panels or modules. According to previous *Figures 34* to *37*, it is responsible for about 35-40% of the total costs in the utility scale and around 50% for the smaller installations. This share is tending to grow in the total cost of PV since modules costs are being reduced drastically and O&M.

To better understand what the BOS concerns, it is attached *Figure 42*, reprinted from *IRENA Renewable Power Generation Costs report in 2014* (IRENA, 2015), which shows all the components of the BOS and its share in the total BOS costs for different countries and types of installation.

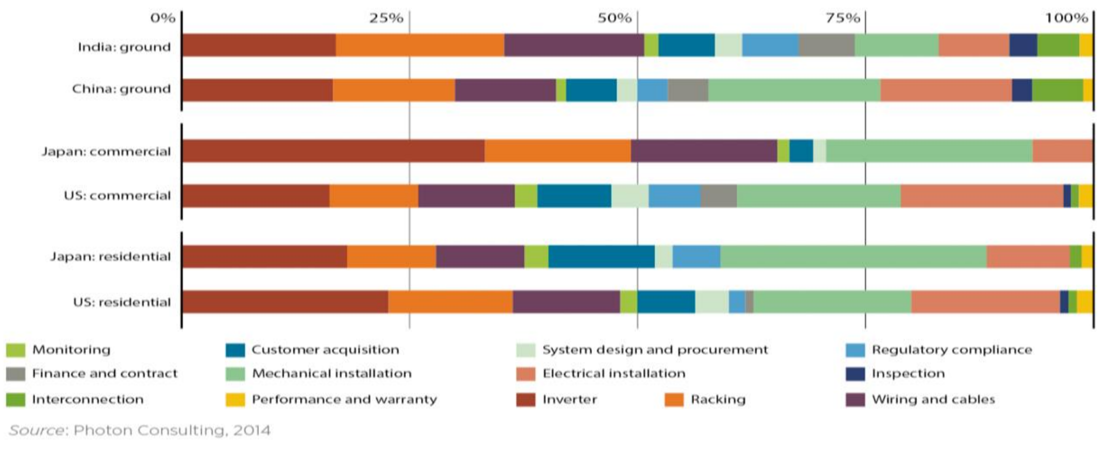


Figure 42. Detailed Balance of System cost breakdown for utility-scale, commercial and residential systems in selected countries, 2014. Reprinted from Renewable Power Generation costs in 2014 (pg 86) by IRENA, 2015.

Supporting *Figure 42*, it is provided *Figure 43*, which shows the relative BOS cost share for a Ground-Mounted System, a Commercial Roof Top system with a pitched roof and a Commercial Roof Top system with a flat roof case. In this representation it can be observed that usually the most impactful concepts are the Substructure and its installation (mechanical installation) and the Inverter + MV + Monitoring. (Ringbeck & Sutterlueti, 2013)

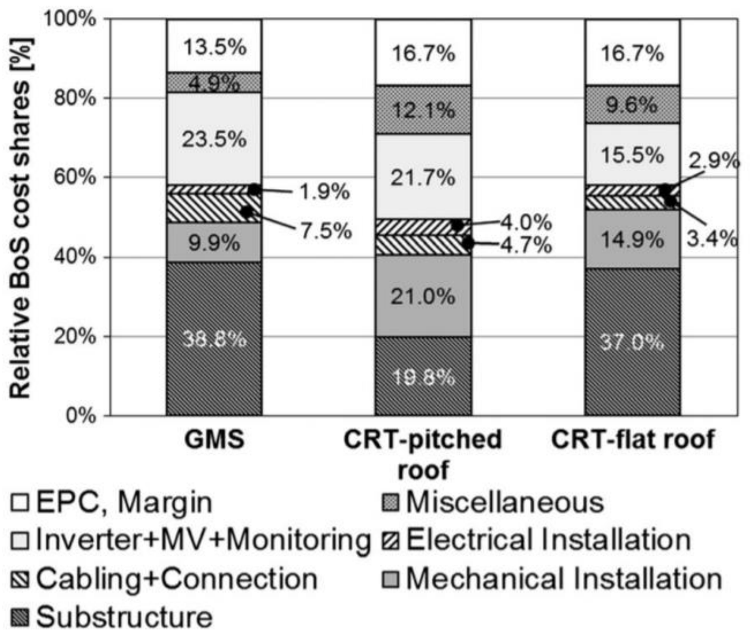


Figure 43. BOS cost share for a GMS, and CRT. Reprinted from BOS costs: status and optimization to reach industrial grid parity (pg 3) by S. Ringbeck and J. Sutterlueti, 2013.

As a global conclusion for the BOS components, it can be observed that the costliest items correspond basically to the inverter, the mechanical and electrical installation together with the margin benefit.

For this reason, since the inverters are also a fundamental part of the installation, which is also experiencing a price reduction with its own trend, it is helpful to isolate the inverter study from the total BOS to better understand its evolution.

In this topic, it is also shown the cost of the BOS in the utility-scale PV systems of different countries which are known for being in the top of the cheapest countries regarding PV installations during the 2018. Such data has been taken from IRENA latest publication (IRENA, 2019). In *Figure 44* it can be observed the BOS costs, concerning both hardware and installation, which is about 0,24 USD $/W in the cheapest cases of Italy and India, and 0,51 USD $/W in the case of France.

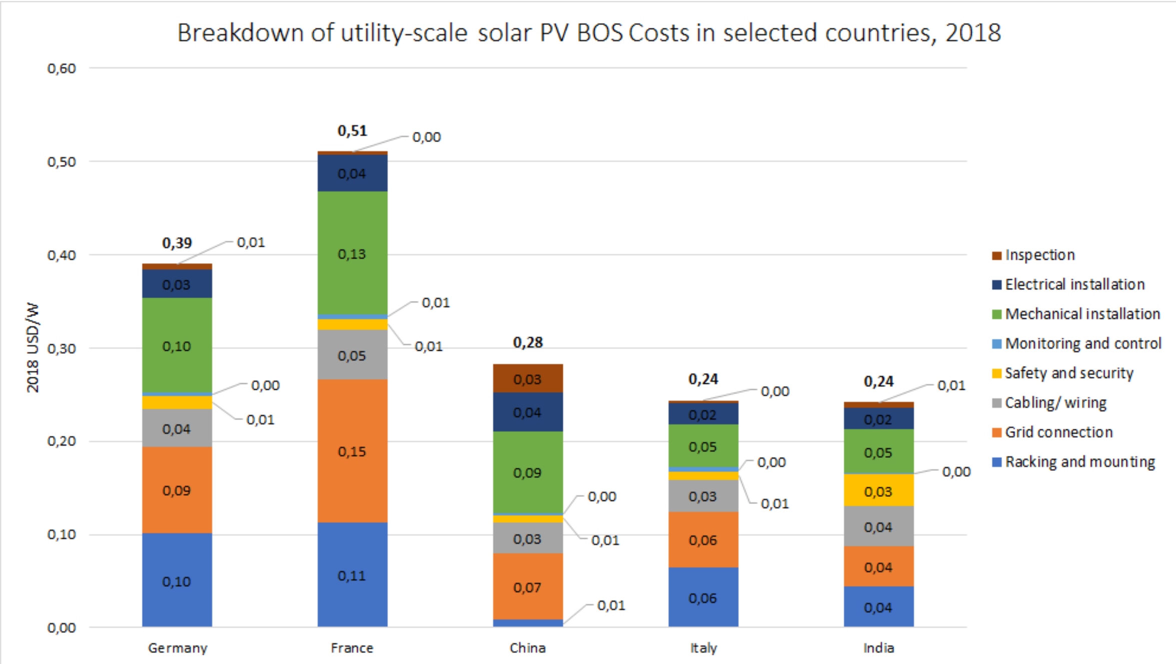


Figure 44. Breakdown of utility-scale solar PV BOS Costs in selected countries, 2018. Own creation based on data from IRENA, 2019.

As it was mentioned before, the BOS is considering all the components in a PV system besides the solar panel and inverter (in this case of study). To help to classify all the components it is common to find two big categories: Structural (or Mechanical) BOS and Electrical BOS.

Mechanical Balance Of System components

As the Pennsylvania State University, College of Earth and Mineral Sciences describes in *Commercial Solar Electric Systems*, *Mechanical BOS Components*, (College of Earth and Mineral Sciences, Pennsylvania State University, 2019) the mechanical components that should be considered in this classification are (or can be):

1. Rails: structure that holds the modules together
2. Splices: to connect rails to each other (Racking)
3. Clamps: to fasten modules to the rails
4. Roof Mount (rooftop with penetration) (Mounting, footings and standoffs)
5. L-foot: structure with screws to fasten the PV array to the rails
6. Tile hooks: direct attachment for equipment to be fastened to the roof
7. Roof Mount (without roof penetration)
8. S-5 clips: to fasten the PV array to a metal roof by biting
9. Applied weight: to hold the array to the roof (concrete or sand)
10. Flashing

Electrical Balance Of System components

On the other hand, in the *Electrical BOS Components* report, it is detailed which components establish the Electrical BOS: (College of Earth and Mineral Sciences, Pennsylvania State University, 2019)

1. Conductors:
    - PV source-circuit wiring
    - PV output-circuit wiring
    - Interior wires
    - Battery wires
    - PV wires
2. Combiner Box (Junction box/combiner)
3. Disconnects
4. (Switchgear and safety/protection devices)
5. Conduits (raceways)
6. Grounding conductors
7. Transformer

8. (Net meter socket)
9. Monitoring system/devices (?)

Structural and Mechanical BOS costs

Once it is described what composes the mechanical and the electrical part of the Balance of System (BOS)it is important to consider the costs regarding such components. Of course, this cost will depend on the scale of the installation, since the more panels are needed more structural support will be required as well. For this reason, it will be important to distinguish these costs depending on the scale.

Thanks to the study carried by NREL on its latest report *US Solar Photovoltaics System Cost Benchmark: Q1 2018* (Fu, Feldman, & Margolis, 2018), it can be summarized the costs depending on the capacity of the installation in the USA in *Table 6*, *7* and *8*:

Table 6. Utility-scale PV Mechanical and Electrical BOS costs for Fixed-Tilt and One-Axis Tracker technology in the U.S.

Utility-scale PV BOS costs			
Type of sun tracking	**Installation Capacity**	**Structural BOS cost (USD/W)**	**Electrical BOS Cost (USD/W)**
Fixed-Tilt	5 MW	0,11	0,17
	10 MW	0,11	0,14
	50 MW	0,10	0,10
	100 MW	0,09	0,08
One-axis tracker	5 MW	0,17	0,17
	10 MW	0,16	0,14
	50 MW	0,15	0,10
	100 MW	0,13	0,08

Note: Own creation based on data from NREL, 2018.

Table 7. Commercial PV Mechanical and Electrical BOS costs for Fixed-Tilt and One-Axis Tracker technology in the U.S

Utility-scale PV BOS costs		
Installation capacity	**Structural BOS cost (USD/W)**	**Electrical BOS Cost (USD/W)**
100 kW	0,12	0,15
200 kW	0,12	0,14
500 kW	0,12	0,13
1 MW	0,12	0,12

Note: Own creation based on data from NREL, 2018.

Table 8. A 6,2 kW Residential PV Mechanical and Electrical BOS costs for Fixed-Tilt and One-Axis Tracker technology in the U.S.

6,2 kW residential PV BOS costs		
Type of inverter option	**Structural BOS Cost (USD/W)**	**Electrical BOS Cost (USD/W)**
String Inverter Option	0,10	0,19
Power Optimizer	0,10	0,18
Microinverter Option	0,10	0,27

Note: Own creation based on data from NREL, 2018.

2.4. Project Development costs: The soft costs, a major factor for the reduced PV scale

Regarding the costs of a Solar PV System, there are several factors to consider besides the hardware components. This is the case of the so-called soft-costs: the non-hardware components such as installation costs, processing costs, distribution costs, etc. The share of such costs among the total costs is plotted in *Figure 45,* showing the share that correspond to the soft costs and to the hardware costs for residential PV systems below 10 kW in some selected countries.

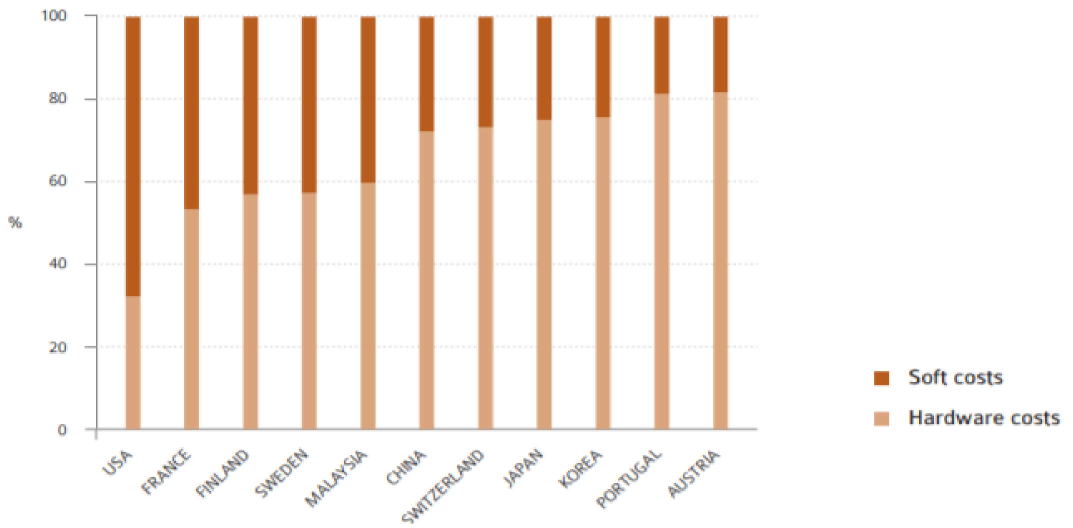


Figure 45. Average cost share breakdown for a residential PV system <10 kW. From Trends 2018 in Photovoltaic Applications (pg 72) by IEA, 2018.

These costs are composed, as Energy Efficiency & Renewable Energy (Energy Efficiency & Renewable Energy, 2019) defines in his report, by different aspects, which are described in the *Figure 46*.

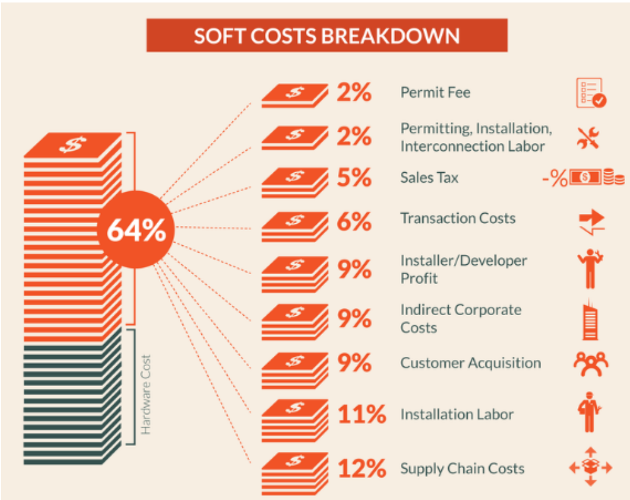


Figure 46. Soft Costs Breakdown for the residential PV systems. Reprinted from Soft Costs (https://www.energy.gov/eere/solar/soft-costs) by Energy Efficiency & Renewable energy, 2016.

As it was pointed previously in previous sections, soft costs account for a big share of the total costs of a PV system, actually, in recent studies elaborated by NREL in *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018* (Fu, Feldman, & Margolis, 2018), it is evaluated that its share may correspond around 63% in the Residential PV systems, a 56% for the Commercial PV systems and a 35% for the utility-scale, in 2018 as *Figure 47* indicates.

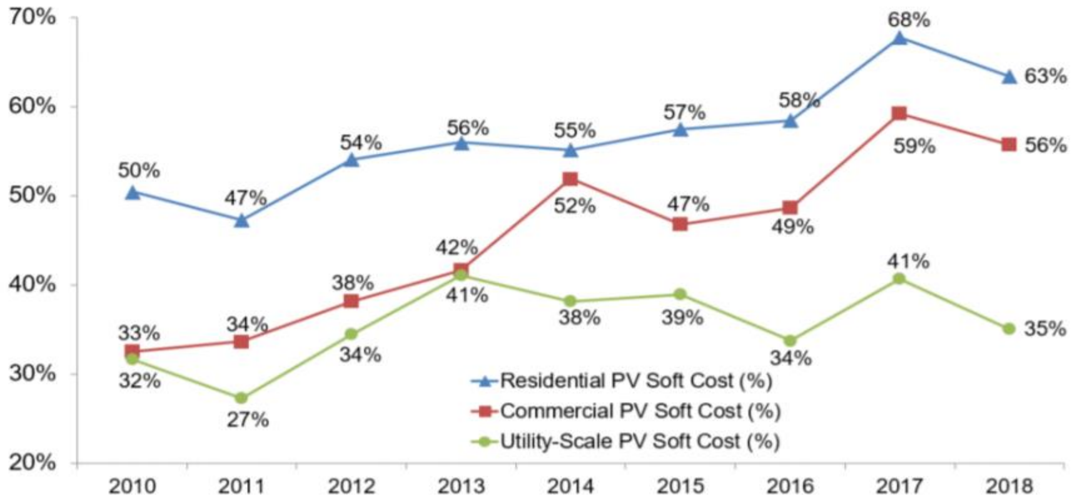


Figure 47. Modeled trend of soft cost as a proportion of total cost by sector 2010-2018. Reprinted from U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (pg 45) by NREL, 2018.

It can be detected that soft-costs have a bigger impact for the reduced scale of these systems, since they involve the non-hardware aspects of the system like the bureaucratic and administrative procedures and taxes which end up having a lower impact when considering large installations with a high investment required. Also, it is clear thanks to *Figure 47* that the share of the total costs for the Soft Costs does not show signs of being reduced or to be reduced soon and this is mainly since all other costs are experiencing a way much faster decrease.

Moreover, taking a deeper look into some of the most advanced and cheapest countries as to the prices of solar PV installations concerns, it is presented the share of these soft cost of the total cost of a utility-scale installation. For this case, it will be presented the costs in Germany and China (*Figure 48* and *49*) from data collected by IRENA (IRENA, 2019), proving that the total share for the Soft Costs accounts for about 17% in the case of Germany and almost 30% for China in the utility-scale perspective. Also, from *Figure 34* we know that the average share for the Soft Costs for 19 selected countries - including Germany and China - is of about 26%.

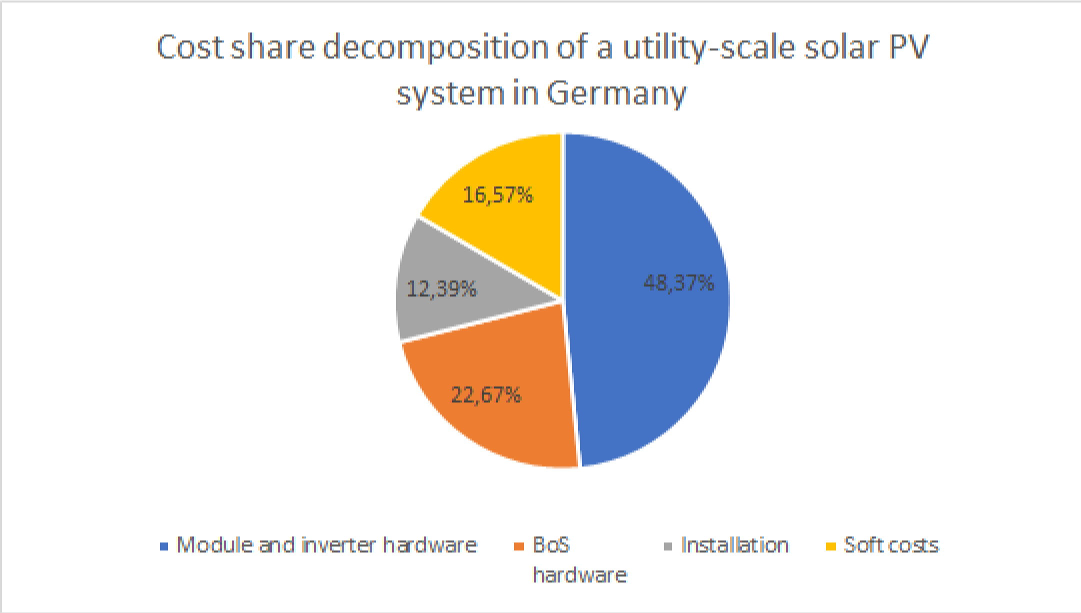


Figure 48. Cost share decomposition of a utility-scale solar PV system in Germany. Own creation based on data from IRENA, 2019.

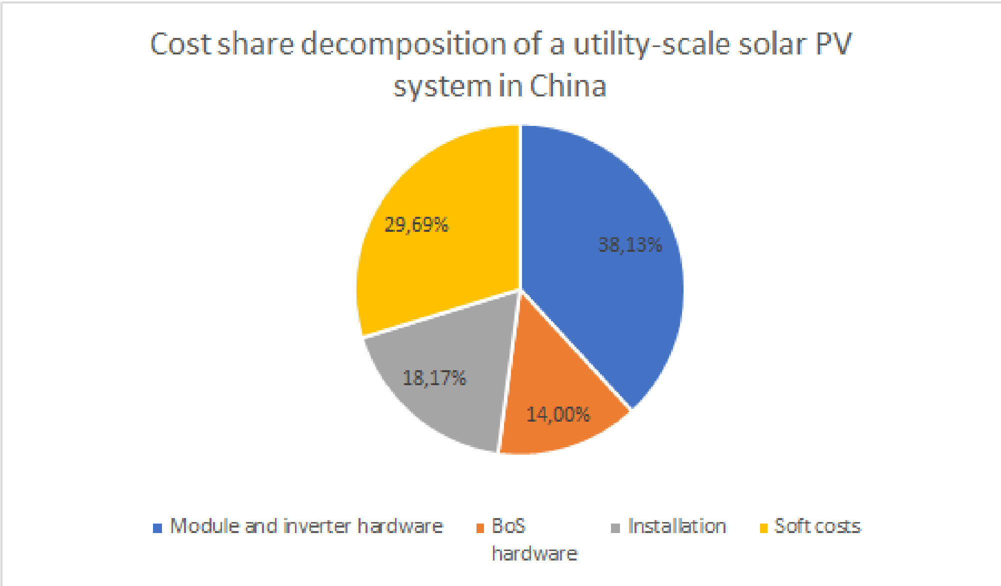


Figure 49. Cost share decomposition of a utility-scale solar PV system in China. Own creation based on data from IRENA, 2019*.*

The fact that such share is so high in China is due the so reduced costs in the manufacturing of the hardware. However, as it will be proved next, these soft costs in China are not the lowest. For that reason, it is important to know which the costs values regarding these soft costs are, and with that focus, it is presented a detailed breakdown of the soft costs in some selected countries with lowest prices: Germany, France, China, Italy and India (*Figure 50*).

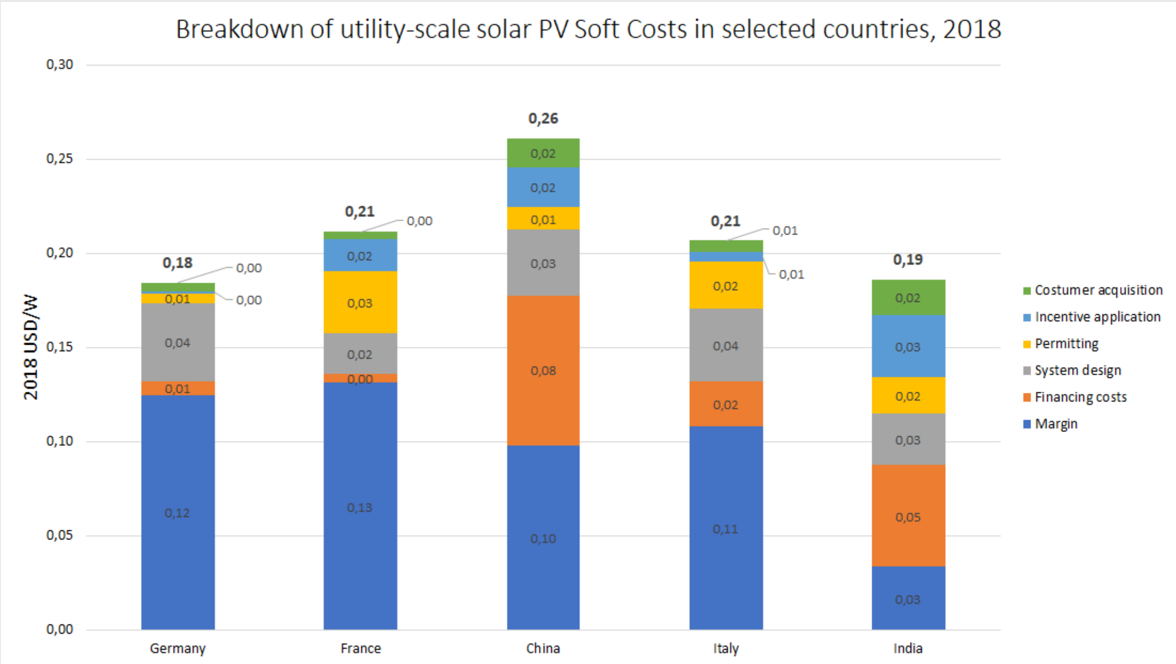


Figure 50. Breakdown of utility-scale solar PV Soft Costs in selected countries, 2018. Own creation based on data from IRENA, 2019.

As it can be observed, in some of the more mature countries in the PV sector, prices in 2018 are around the range of 0,26 - 0,42 USD/W. Being the margin of benefit the main driver to such costs. Also, it is having a big impact on the prices the mechanical installation and electrical.

Since such costs are associated with customer acquisition, permitting, inspection, interconnection, supply chain and other overhead costs, which are dependent on the legislation and local policies, they do not seem to have a clear spotlight to create reductions in this sector. However, some of the countries are starting to improve the permitting, inspection and interconnection to the grid processes and evolving towards an ease of the procedure and reduction of these costs. Though, this is an area which can be quite different on each of the countries and for that reason is difficult to determine how this cost trend will evolve in future years.

The fact that Soft Costs have not been reduced as much as the other categories of a PV installation is now provoking most of the companies of the sector to start concerning about trying to investigate how could be possible to reduce its costs. Since they account for a great part of the total costs, Soft Costs is considered the biggest cost-decline opportunity in the residential and small commercial solar sector (SEIA, 2019). Such cost share evolution, in the residential scale, can be better understood thanks to *Figure 51*, where it can be observed that the share trend for the Soft Costs is to increase.

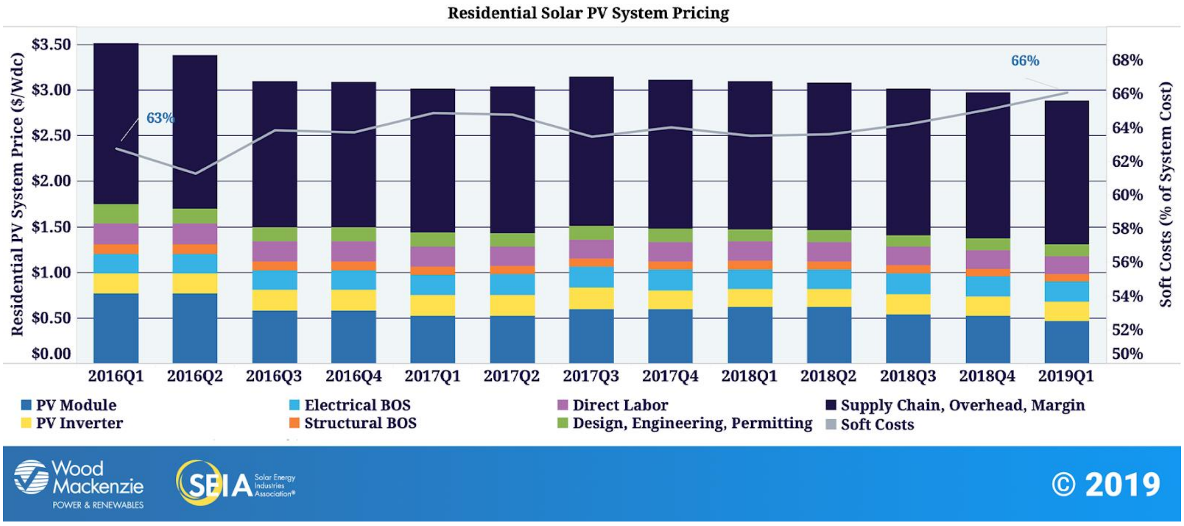


Figure 51. Residential Solar PV System Pricing. Reprinted from Solar Industry Research Data, Soft Costs - A Major Opportunity for Residential Price Decline (https://www.seia.org/solar-industry-research-data) by SEIA, 2019.

2.5. Final costs of the Solar Energy to the consumer: the LCOE

The *LCOE* is a convenient tool for comparing the unit costs of different technologies over their economic life (OECD, NEA/IEA, 2010). The LCOE methodology is an abstraction from reality and is used as a benchmarking or ranking tool to assess the cost-effectiveness of different energy generation technologies (Branker, Pathak, & Pearce, 2011). Estimation of the LCOE of renewables is the basis of the appropriate Feed-In-Tariffs.

All the costs involved in a PV installation have an influence in the final cost of the energy, which is best explained thanks to the Levelized Cost Of Energy (LCOE). Therefore, similarly to the trends of the costs already explained, the LCOE has been experiencing a reduction in a close-to-linear way. This evolution is explained by IRENA taking the case of residential installations -from 0 to 10 kW- of some of the leading countries in PV systems technology in *Figure 52*, where it can be observed the LCOE variation from Q2 2007 to Q1 2017. (IRENA, 2018)

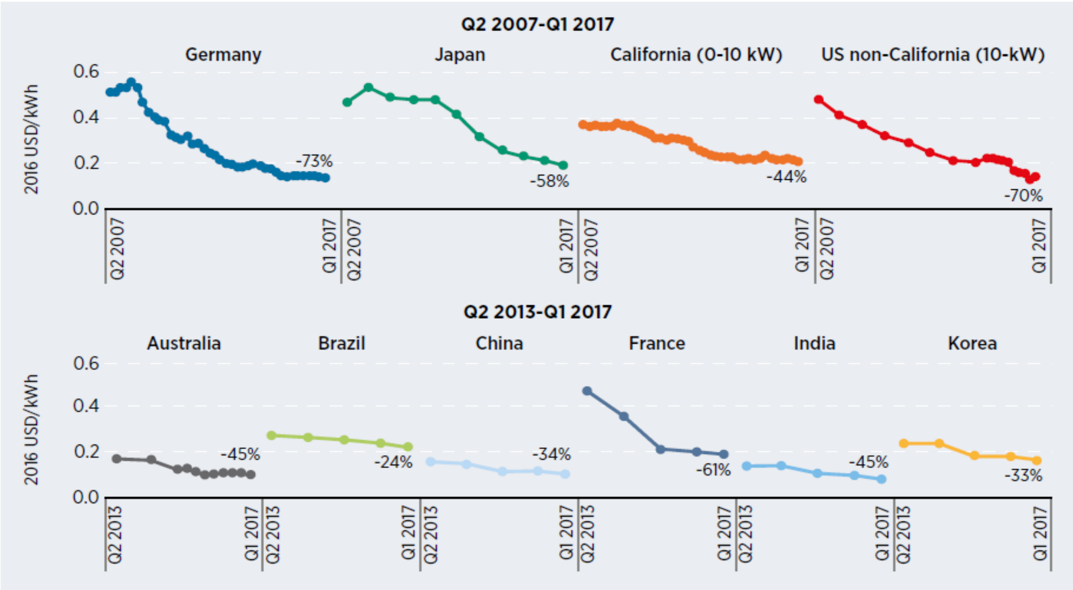


Figure 52. Levelized cost of electricity from residential solar PV systems by country, Q2 2007-Q1 2017. Reprinted from Renewable Power Generation Costs in 2017 (pg 72) by IRENA, 2018.

In the introduction of the paper, the solar LCOE was shown as to compare the different energy resources. Although it was a representative value, it was a general approximation which did not distinguish between the type of solar facility, which indeed is one of the goals of this paper. In *Lazard's Levelized Cost of Energy v.12* (LAZARD, 2018), a specific LCOE study is conducted not just for solar but for other energy resources (conventional and renewable). In this case, they made a differentiation of the values, just in the USA, depending on the facility output.

In addition, it is discriminated the values whether they are under U.S. Federal Tax Subsidies conditions or not, *Figure 53*. However, the difference between being subsidized or not does not make a significant difference, only in the Rooftop Residential case.

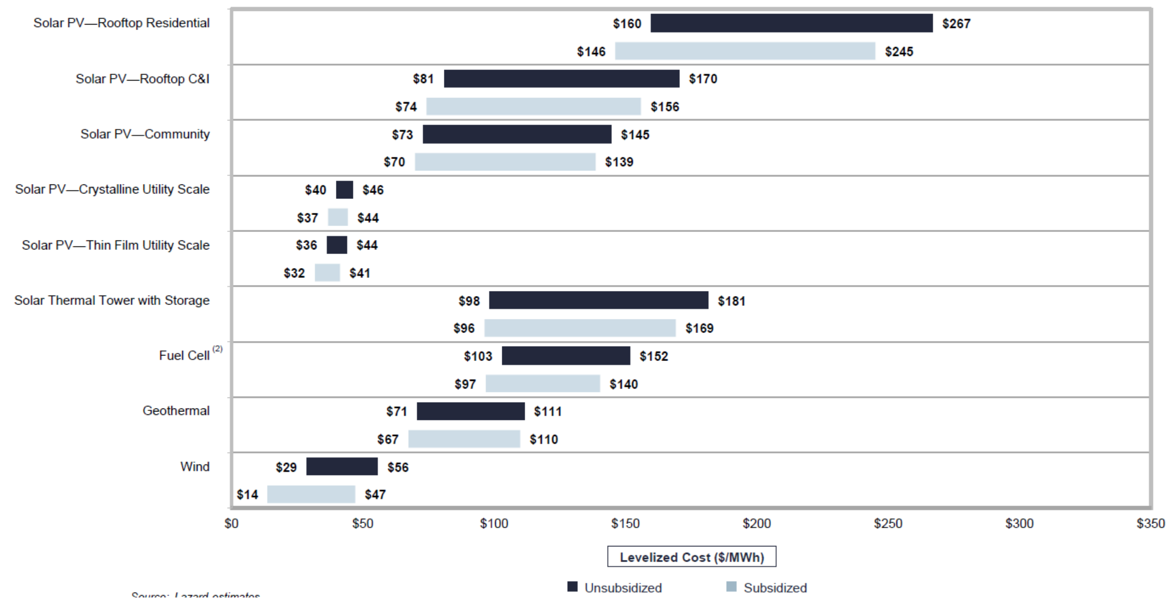


Figure 53. LCOE Comparison - Sensitivity to US Federal Tax Subsidies. Reprinted from Lazard's Levelized Cost Of Energy Analysis - Version 12.0 by Lazard, 2018.

Making a deeper analysis in the three main cases of Solar PV sectors: utility-scale, commercial and residential, NREL developed a report (*U.S. Photovoltaic System Cost Benchmark: Q1 2018*) in which it is presented the LCOE evolution of the PV systems. Such classification considers:

- Utility-scale Solar PV System (> 2 MW): Generally ground-mounted
- Commercial Solar PV System (10 kW - 2 MW): Placed on large buildings or complexes
- Residential Building Solar PV System (3 - 10 kW): Usually roof-mounted.

As the *Figure 54*, *55*, *56* indicate, the three sectors seem to have a very similar trend while confirming that the residential field is the one that implies more expenses per watt installed, since its low capacity does not allow the economy scale to reduce its prices as much as the other scales can.

Figure 54. LCOE for utility-scale PV systems, by region, with and without ITC (Investment Tax Credit) 2010 – 2018. Reprinted from U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (pg 39), 2018.

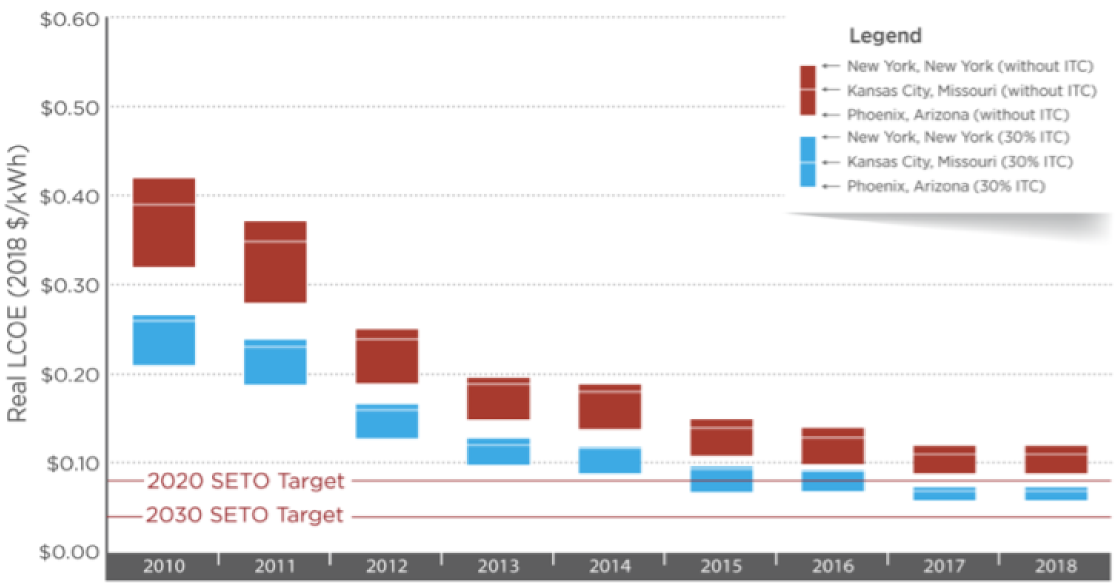


Figure 55. LCOE for commercial PV systems, by region, with and without ITC, 2010 - 2018. Reprinted from U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (pg 29), 2018.

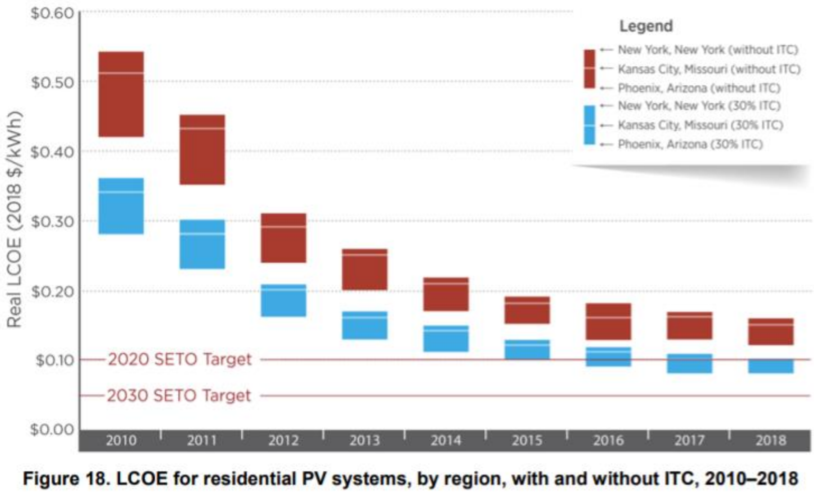


Figure 56. LCOE for residential PV systems, by region, with and without, 2010 - 2018. Reprinted from U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (pg 23) by NREL, 2018.

In more precision, it is found the LCOE evolution trend evaluated by for the utility-scale case (LAZARD, 2018) in *Figure 57* where it can be observed a great reduction of the unsubsidized LCOE for the crystalline technology reaching prices in the range of $46 - 40/MWh in 2018.

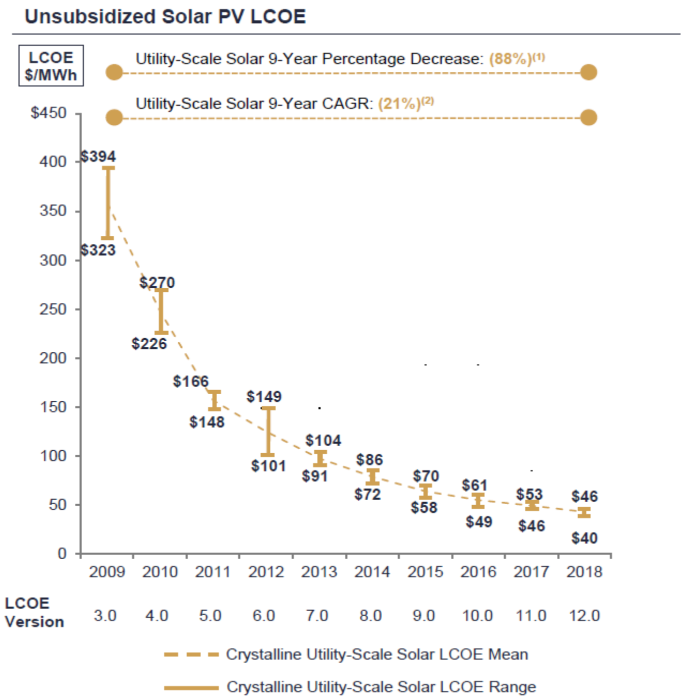


Figure 57. Unsubsidized Solar PV LCOE for Utility-Scale facility. Reprinted from Lazard's Levelized Cost of Energy Analysis - v.12 (pg 8) by Lazard, 2018.

Moreover, this trend is expected to continue this linearity: IRENA explains in the report *Renewable Power Generation Costs in 2017* (IRENA, 2018), where, thanks to the learning curves method, it is predicted the LCOE of the different renewables and compared to the fossil fuel cost range. As *Figure 58* shows, it is expected that such renewable sources could reach the prices as low as the cheapest fossil fuels, especially in the case of PV and onshore wind by 2020. (IRENA, 2018)

In the report (IRENA, 2018), it is also explained that such reductions are expected to happen due to three major factors: the technology improvements, the competitive procurement and the large base of experienced and active developers. What is more, the results of recent renewable power auctions confirm that cost reductions are set to continue beyond the 2020.

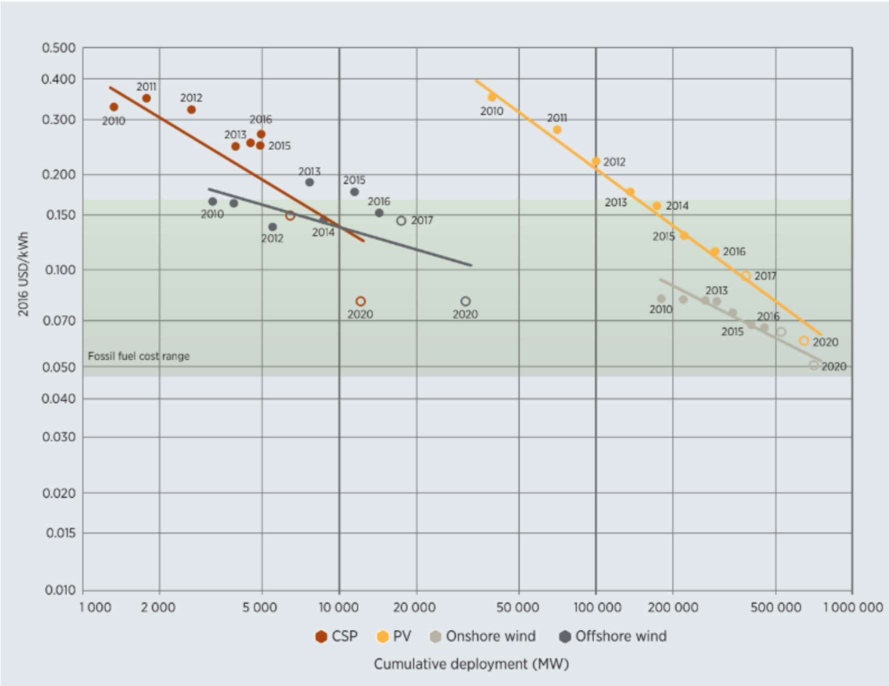


Figure 58. LCOE reduction and prediction for 2020 by means of learning curves for renewable energies. Reprinted from Renewable Power Generation Costs in 2017 (pg 53) IRENA, 2018.

2.6. Solar PV Projects Costs for different scales: the huge impact of the economy of scale

The projects can change its cost structure according to the size of the installation. For the larger projects, the utility-scale systems, it is usually used a centralized inverter of around 0,75 - 1,5 MW with some transformers which increase the voltage of the panels arrays to centralize it and then elevate it to transmission levels.

Moreover, since the small-scale projects (< 1 MW) can usually connect to the distribution network they do not require the MT/AT transformer and for that reason their costs structure vary from the projects which really need it. The prices of distribution are much higher, which modifies either the incomes and costs of the projects. The case of the small residential projects (1 - 2 kW), is marked by the soft costs, installation costs, processing and others, which become the dominant components for the total costs. Likewise, the trade prices for the energy are much higher, modifying the variability of such projects.

For the evaluation of the different scale projects, it will be considered the 3 main categories of installations used by NREL in the *U.S. Solar Photovoltaic System Cost Benchmark* (Fu, Feldman, & Margolis, 2018) which differ in the total power installed:

1. Utility-scale Solar PV System (> 2 MW): Generally, ground-mounted
2. Commercial Solar PV System (10 kW - 2 MW): Placed on large buildings or complexes
3. Residential Building Solar PV System (3 - 10 kW): Usually roof-mounted.

Regarding each type of scale PV system, it is worth looking at the amount of installations developed of each of the categories from 2010 to 2017 in the USA, a reference case. Thanks to *Figure 59*, it can detect an increasing trend on the total PV systems installed and an exceptional quantity of Utility-scale PV systems installed, especially during 2016. However, such trend was stopped in 2017 even though a great amount of PV installations were developed, and it is also relevant to remark how thriving has been recently the Residential PV market.

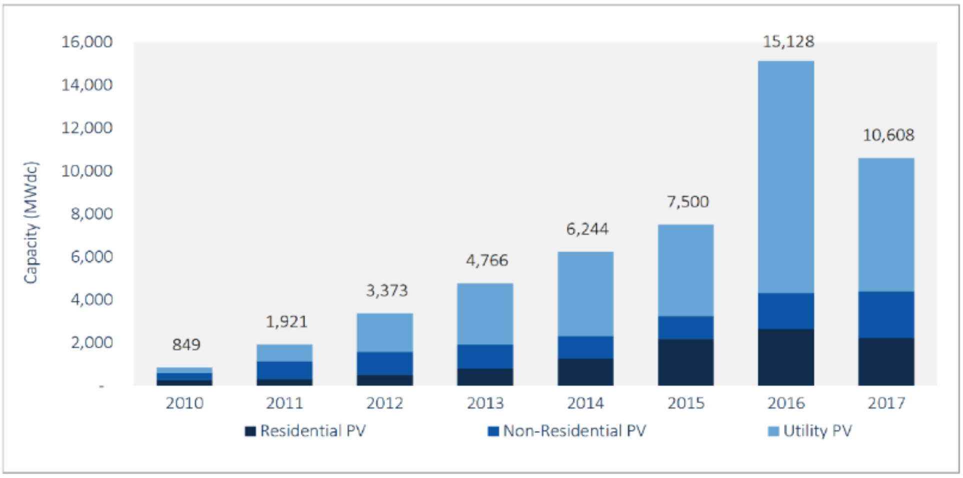


Figure 59. US Annual PV Installations 2010-2017. Reprinted from U.S. Solar Market Insight, Executive Summary 2017 Year in Review (pg 6) by SEIA, 2017.

Moreover, in order to have a general idea of the total costs that each type of installation is involves, Lazard presents a summary table (LAZARD, 2018), *Table 9*, where the most important parameters regarding a solar project, concerning both economic and technical aspects. The table is divided into the type of facility: Residential, Commercial and Utility Scale. As read in literature, the numbers appearing in the table give proof that, although they have always to be considered, O&M costs are not significant since its cost per kW-year is low.

Table 9. Levelized Cost Of Energy and Key Parameters for Different Installation Sizes.

Solar PV						
Feature	**Units**	**Rooftop - Residential**	**Rooftop – C&I**	**Community**	**Utility-scale - Crystalline**	**Utility-scale - Thin Film**
Net-facility Output	MW	0.005	1	5	50	50
Total Capital Cost	$/kW	2,950 – 3,250	1,900 – 3,250	1,850 – 3,000	1,250 – 950	1,250 – 950
Fixed O&M	$/kW-yr	14.50 – 25.00	15.00 – 20.00	12.00 – 16.00	12.00 – 9.00	12.00 - 9.00
Variable O&M	$/MWh	-	-	-	-	-
Heat Rate	Btu/kWh	-	-	-	-	-
Capacity Factor	%	19 – 13	25 – 20	25 – 20	32 – 21	34 – 23
Fuel Price	$/MMBtu	-	-	-	-	-
Construction Time	Months	3	3	4 – 6	9	9
Facility Time	Years	25	25	30	30	30
Levelized Cost of Energy	$/MWh	160 – 267	81 – 170	73 – 145	40 – 46	36 - 44

Note: Reprinted from Lazard's Levelized Cost of Energy Analysis - Version 12.0 (pg 16) by Lazard, 2018.

2.6.1. Utility-scale Solar PV Systems Costs

Those systems accounting installation capacity greater than 2 MW are considered as utility-scale systems, which is the bigger scale in the PV installations (Fu, Feldman, & Margolis, 2018). Such utility-scale systems are marked by the effect of the economy of scale: since big capacity installation it is possible to cut prices when purchasing substantial quantities of the technology needed, like solar panels, inverters, etc. For this reason, the price per unit of power of this type of installation is considerably lower than the other two.

However, the fact that hardware technology prices can be cut off, does not make them be a minor share of the total costs; for the bigger scale PV systems, as it has been shown previously in *Figure 34*, it is known that most of the costs of the installation comes from the solar panels and inverters.

With the purpose to analyze the cost of the categories that compose an installation and to evaluate its total costs and evolution trend, NREL developed a study in the report *US Solar Photovoltaic System Cost Benchmark: Q1 2018 (NREL)* (Fu, Feldman, & Margolis, 2018), where a baseline system of 100MW utility scale system model in the USA is considered and defined in *Table 10*.

Table 10. Utility-Scale PV: Modeling Inputs and Assumptions

Category	Modeled Value	Description	Sources
System size	5-100 MW	A large utility-scale system capacity	Model assumption
Module efficiency	19.1%	Average module efficiency	NREL (2018)
Module price	$0.47/Wdc	Ex-factory gate (first buyer) price, Tier 1 modules	GTM and SEIA (2018), NREL (2018)
Inverter price	$0.04/Wdc (fixed-tilt) $0.05/Wdc (one-axis tracker)	Ex-factory gate (first buyer) price, Tier 1 inverters DC-to-AC ratio = 1.36 for fixed-tilt and 1.30 for one-axis tracker	Bloomberg (2018), Bolinger and Seel (2018), NREL (2018)
Structural components (racking)	$0.10–$0.21/Wdc for a 100-MW system; varies by location and system size	Fixed-tilt racking or one-axis tracking system	ASCE (2006), model assumptions, NREL (2018)
Electrical components	Varies by location and system size	Our model has been upgraded to 1,500 Vdc system, including conductors, conduit and fittings, transition boxes, switchgear, panel boards, onsite transmission, etc.	Model assumptions, NREL (2018), RSMeans (2018)
EPC overhead (% of equipment costs)	8.67%–13% for equipment and material (except for transmission line costs); 23%–69% for labor costs; varies by system size, labor activity, and location	Costs associated with EPC SG&A, warehousing, shipping, and logistics	NREL (2018)
Sales tax	Varies by location	National benchmark applies an average (by state) weighted by 2017 installed capacities	RSMeans (2018), GTM and SEIA (2018)
Direct installation labor	Electrician: $19.74–$38.96 per hour; Laborer: $12.88–$25.57 per hour; Varies by location	Modeled labor rate assumes both non-union and union labor and depends on state; national benchmark uses weighted average of state rates	BLS (2018), NREL (2018)

Burden rates (% of direct labor)	Total nationwide average: 31.8%	Workers compensation (state-weighted average), federal and state unemployment insurance, FICA, builders' risk, public liability	RSMeans (2018)
PII	$0.03–$0.09/Wdc Varies by system size and location	For construction permits fee, interconnection, testing, and commissioning	NREL (2018)
Transmission line (gen-tie line)	$0.00–$0.02/Wdc Varies by system size	System size < 10 MW; use 0 miles for gen-tie line System size > 200 MW; use 5 miles for gen-tie line System size = 10–200 MW; use linear interpolation	Model assumptions, NREL (2018)
Developer overhead	2%–12% Varies by system size (100 MW uses 2%; 5 MW uses 12%)	Includes overhead expenses such as payroll, facilities, travel, legal fees, administrative, business development, finance, and other corporate functions	Model assumptions, NREL (2018)
Contingency	3%	Estimated as markup on EPC cost	NREL (2018)
Profit	5%–8% Varies by system size (100 MW uses 5%; 5 MW uses 8%)	Applies a percentage margin to all costs including hardware, installation labor, EPC overhead, developer overhead, etc.	NREL (2018)

Note: Reprinted from U.S. Photovoltaic System Cost Benchmark: Q1 2018 (pg 31) by NREL, 2018.

Considering all the features described above in *Table 10*, NREL evaluated its costs also considering different sizes of installation and two different technologies of sun tracking. The costs variations depending on the magnitude of the utility-scale installation are presented in *Figure 60*; such graphic allow to understand which is the component that accounts for the major share of the total costs, which is the module. However, it can be observed that the module price does not vary as the capacity of the installation is increased, meaning that, for NREL, the usage of more modules does not bring a reduction on their price due to the economies of scale.

On the other hand, it can be observed that this scale increase brings total costs reduction, which could be accounted for most of the components excepting the inverter and Sale Taxes. For that reason, it can be concluded that the increase of the capacity in these other factors leads to a cost reduction, which is a logic behavior.

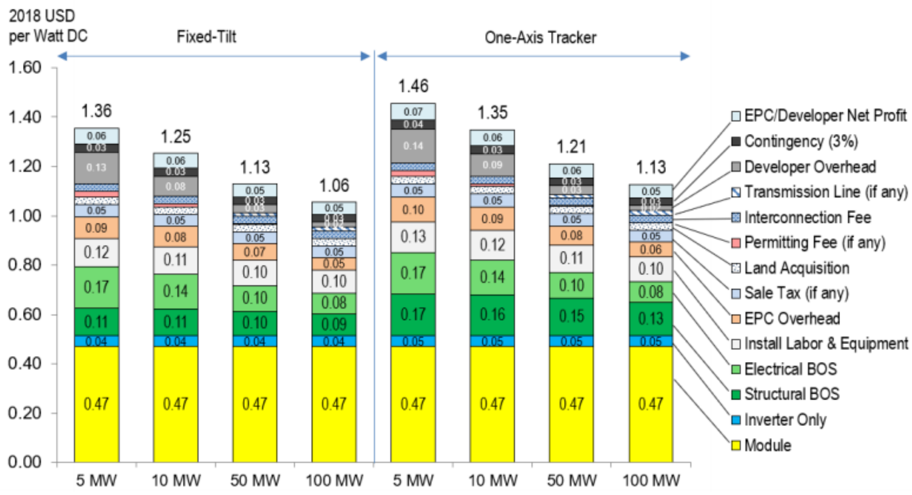


Figure 60. Q1 2018 U.S. benchmark: utility-scale PV total cost, 2018 USD/Wdc. Reprinted from U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (pg 36) by NREL, 2018.

In order to make a comparison of the costs over the year and, therefore, be able to see its evolution, the 100 MW installation system is considered. This costs evolution in the recent years is illustrated in *Figure 61*, where it is shown the reduction on the utility-scale PV system cost benchmarks between 2010 and 2018 (Fu, Feldman, & Margolis, 2018). The reduction within that period was of 77% for fixed tilt and 80% for one-axis tracking, mainly due to total hardware costs since during this period the module prices dropped around 81%. *NREL* attributes another 11% for the fixed-tilt case, and 12% for the one-axis tracking, to the labor costs reduction. The rest are related to other soft costs: sales tax, overhead and net profit. (Energy Efficiency & Renewable Energy, 2019)

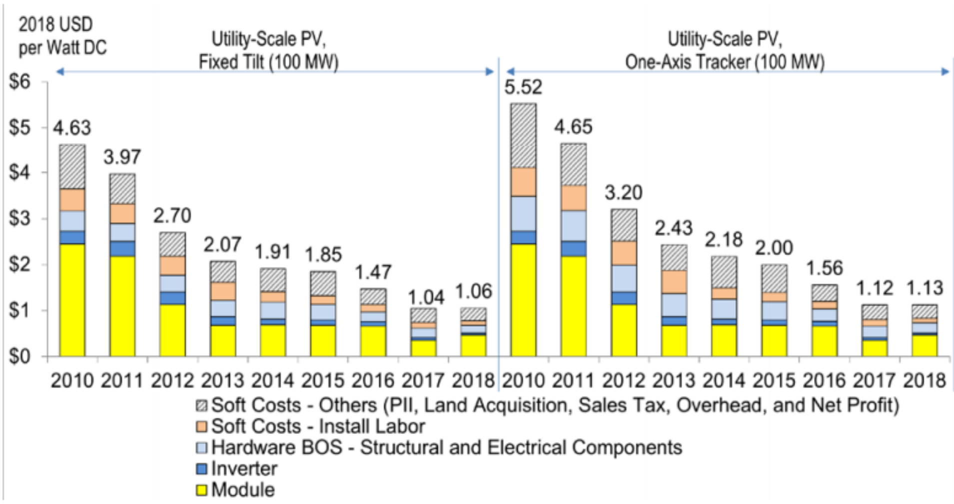


Figure 61. NREL utility-scale PV system cost benchmark summary, 2010-2018. Reprinted from U.S. Photovoltaic System Cost Benchmark: Q1 2018 (pg 37) by NREL, 2018.

However, it can be detected a small increase on the costs from 2017 to 2018, which is mainly due to the great increase in the module spot price in USA, which offset cost reductions in the other areas (Fu, Feldman, & Margolis, 2018). Even though, the cost benchmark trend is expected to continue to decrease for the following years even though that is not going to be as pronounced as it has been in the past years.

This evolution has not only occurred in the USA but also in a global approach. As IRENA demonstrates in the report *Renewable Power Generation Costs in 2017* (IRENA, 2018), the global trend from the last few years has as well been to decrease in an impressive manner. As *Figure 62* proves, it can be seen the increase of projects installed each of the years between 2010 and 2017 and the corresponding cost decrease: a 68% cost decrease from 2010 until 2017. (IRENA, 2018)

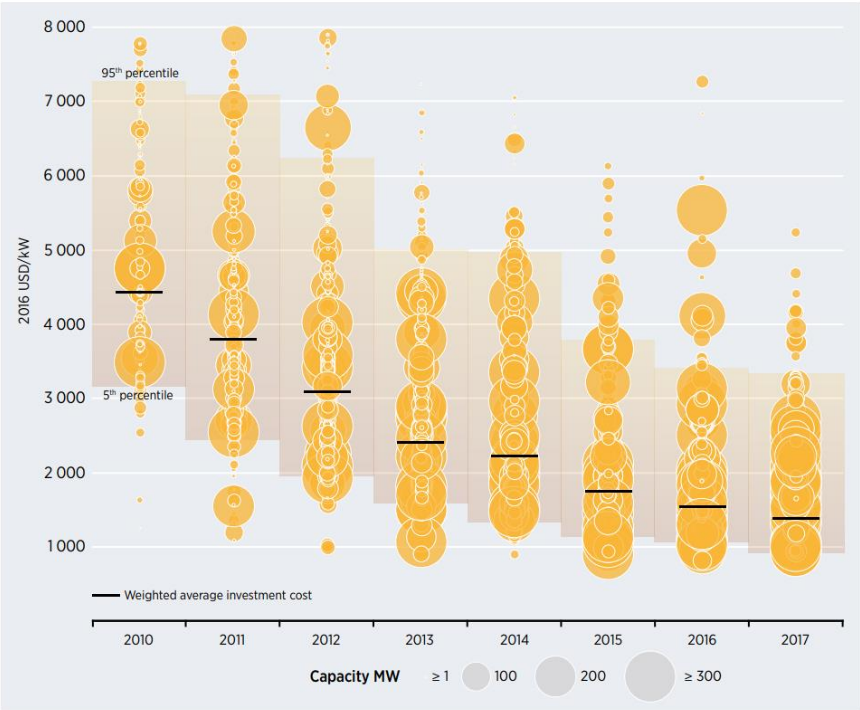


Figure 62. Total installed costs for utility-scale solar PV projects and the global weighted average, 2010-2017. Reprinted from Renewable Power Generation Costs in 2017 (pg 64) by IRENA, 2018.

In a more detailed description, IRENA also shows the individual decreasing evolution in prices of Utility-scale PV (IRENA, 2018) systems for 8 selected countries in *Figure 63*. As it can be observed, the US appears to be one of the countries with the lowest cost decrease since 2010 with “only” a 52% reduction, while the other countries overcome the 70%.

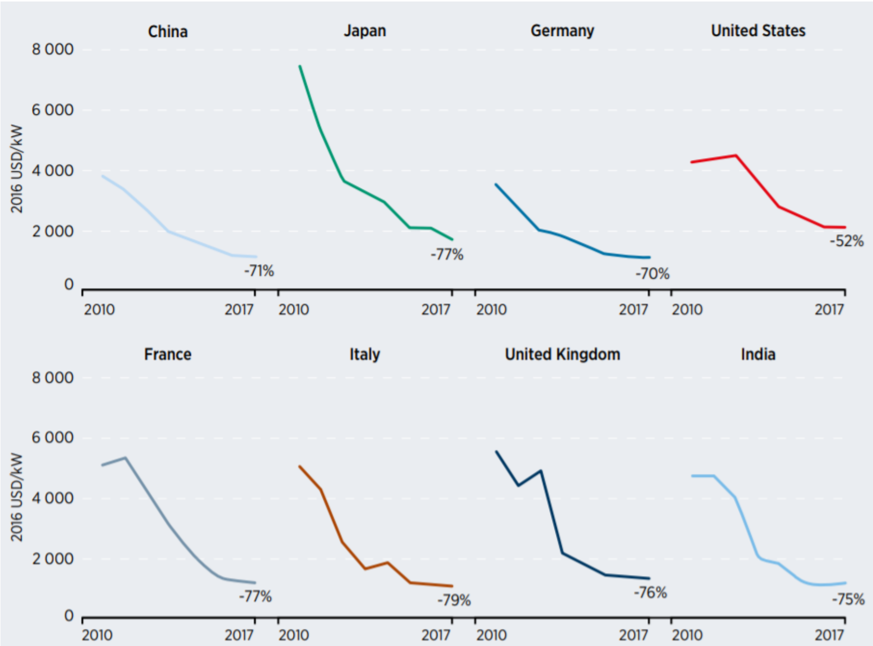


Figure 63. Utility-scale solar PV total installed cost trends in selected countries, 2010-2017. Reprinted from Renewable Power Generation Costs in 2017 (pg 65) by IRENA, 2018

2.6.2. Commercial Solar PV System

The systems accounting an installation capacity ranging between 10 kW and 2 MW are considered as Commercial Solar PV Systems. (Fu, Feldman, & Margolis, 2018) This type of projects is characterized for being of smaller size than the utility-scale but still not considered residential, making them not able to benefit from the economy scale as much as the large systems and increasing, this way, prices per unit of power are higher. Moreover, the impact of the Soft Cost in for that category will be higher, since this type of costs have a lower influence coming from the different sizes of an installation.

In order to evaluate the total costs and the costs of all the components present in a commercial PV system and following the same procedure to the Utility-scale, a base-line is designed by NREL in *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018 (NREL)* (Fu, Feldman, & Margolis, 2018) for the commercial systems in order to make an analysis of the evolution of the cost benchmark. All the features considered are described below in the *Table 11*.

Table 11. Commercial PV: Modeling Inputs and Assumptions.

Category	Modeled Value	Description	Sources
System size	100 kW–1 MW	Average installed size per system	Go Solar CA (2018)
Module efficiency	19.1%	Average module efficiency	Go Solar CA (2018)
Module price	$0.47/Wdc	Ex-factory gate (first buyer) ASP, Tier 1 modules	GTM and SEIA (2018), NREL (2018)
Inverter price	Three-phase string inverter: $0.08/Wdc	Ex-factory gate prices (first buyer) ASP, Tier 1 inverters	PVinsights (2018), NREL (2018)
Structural components (racking)	$0.10–$0.22/Wdc; varies by location due to wind and snow loading	Ex-factory gate prices; flat-roof ballasted racking system	ASCE (2006), model assumptions, NREL (2018)
Electrical components	$0.13–$0.17/Wdc; varies by location due to cost of doing business	Conductors, conduit and fittings, transition boxes, switchgear, panel boards, etc.	Model assumptions, NREL (2018), RSMeans (2018)
EPC overhead (% of equipment costs)	13%	Costs and fees associated with EPC overhead, inventory, shipping, and handling	NREL (2018)
Sales tax	Varies by location	Sales tax on equipment costs; national benchmark applies an average (by state) weighted by 2017 installed capacities	RSMeans (2018), GTM and SEIA (2018)
Direct installation labor	Electrician: $19.74–$38.96 per hour; Laborer: $12.88–$25.57 per hour; Varies by location	Modeled labor rate assumes non-union labor and depends on state; national benchmark uses weighted average of state rates	BLS (2018), NREL (2018)
Burden rates (% of direct labor)	Total nationwide average: 31.8%	Workers compensation (state-weighted average), federal and state unemployment insurance, FICA, builders' risk, public liability	RSMeans (2018)
PII	$0.10/Wdc	For construction permits fee, interconnection study fees for existing substation, testing, and commissioning	NREL (2018)
Developer overhead	Assume 10-MW system development and installation per year for a typical developer	Includes fixed overhead expenses such as payroll, facilities, travel, insurance, administrative, business development, finance, and other corporate functions; assumes 10 MW/year of system sales	Model assumptions, NREL (2018)
Contingency	4%	Estimated as markup on EPC cost; value represents actual cost overruns above estimated cost	NREL (2018)
Profit	7%	Applies a fixed percentage margin to all costs including hardware, installation labor, EPC overhead, developer overhead, etc.	NREL (2018)

Note: Reprinted from U.S. Photovoltaic System Cost Benchmark: Q1 2018 (pg 25) by NREL, 2018.

With the considered inputs and assumptions, it is presented the benchmark costs for the commercial PV system for different capacity sizes, as presented in the *Figure 64*. Again, like in the utility-scale case of study, it can be observed no variation in the module's prices when the capacity of the installation is increased, which accounts for the biggest share of the total costs, and the same happens for the Developer Overhead and the Structural BOS and Inverter. On the other hand, there is a reduction in all the other components that compose the whole costs when the size of the installation increases, which make larger systems less costly per unit of power installed.

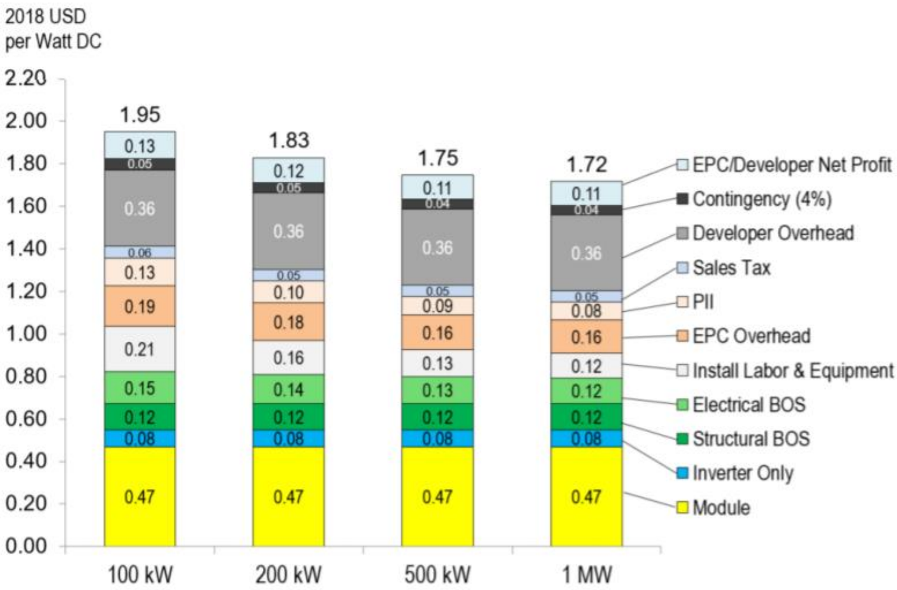


Figure 64. Q1 2018 U.S. benchmark: commercial PV system cost (2018 USD/Wdc). Reprinted from U.S. Photovoltaic System Cost Benchmark: Q1 2018 (pg 26) by NREL, 2018.

The evolution of the costs for commercial PV systems since 2010 to 2018 is presented by NREL (Fu, Feldman, & Margolis, 2018) as well. As *Figure 65* demonstrates, the costs for this sector has been reduced by about 66% since 2010. The 79% of such reduction comes from the hardware costs (module, inverter and hardware BOS) which is mainly due to the drop of the module's prices of an 82%. Another 5% is on the labor costs, which dropped about 50% and the final 16% is due to the soft cost's reduction.

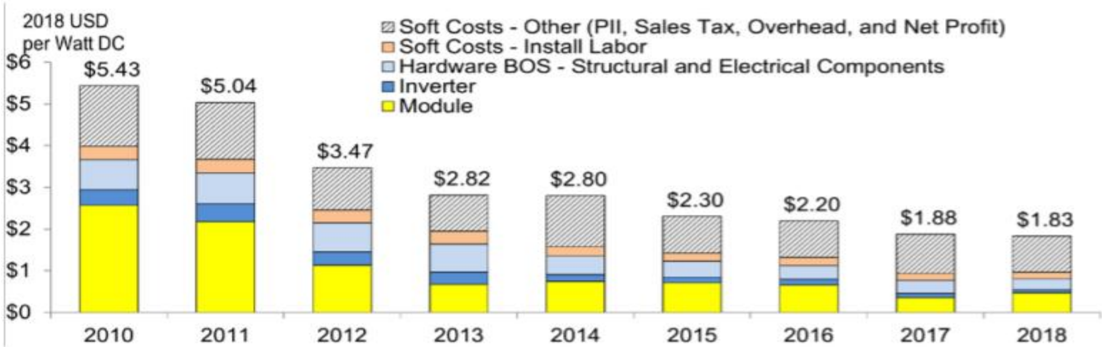


Figure 65. NREL commercial PV system cost benchmark summary, 2010-2018. Reprinted from U.S. Photovoltaic System Cost Benchmark: Q1 2018 (pg 27) by NREL, 2018.

This evolution trend has also been similar for the case of Australia. As *Solar Choice* database demonstrates (Solar Choice, 2019), plotted in *Figure 66*, the prices decreased impressively until nowadays. However, it can be observed a lower reduction in prices in the last few years, indicating that the technology is reaching a certain point of maturity.

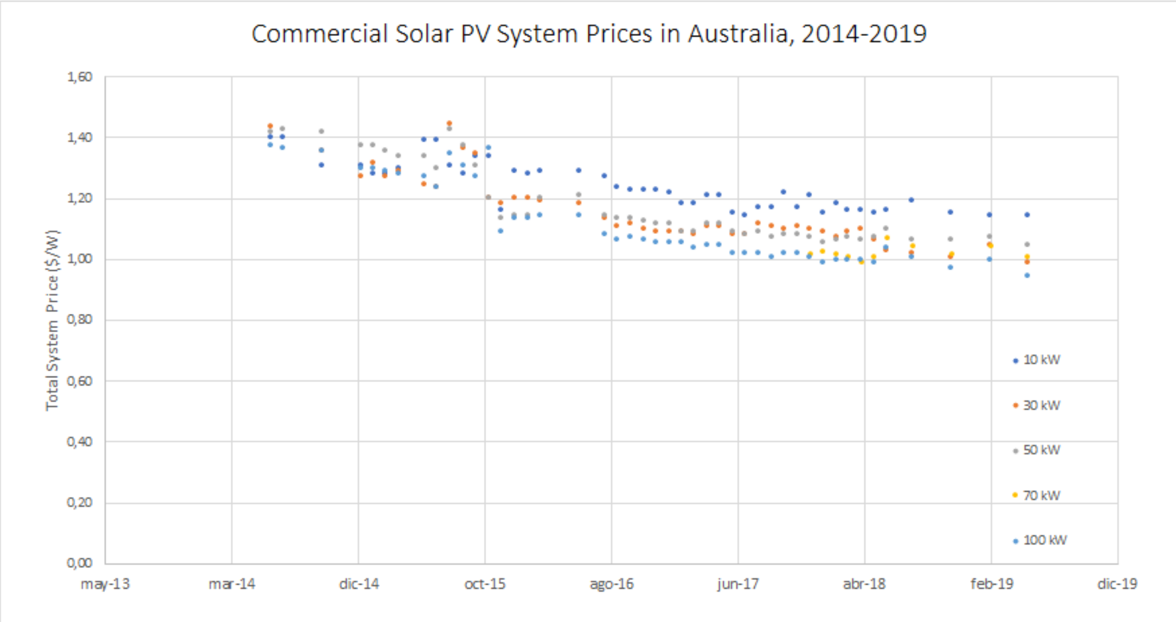


Figure 66. Commercial Solar PV System Prices in Australia, 2014-2019. Own creation based on data from Solar Choice, 2019

2.6.3. Residential Solar PV Systems

The systems accounting an installation capacity below 10 kW are considered as Residential Solar PV Systems. These are the smaller systems which get highly influenced by the Soft Costs and for the lowest capacity to reduce cost due to economies of scale. For that reason, Residential Solar PV Systems are the most expensive projects regarding the price per power installed. (Fu, Feldman, & Margolis, 2018) For the analysis of the costs and components of the installation, a similar evaluation is made by NREL, considering all the cost of the concepts that are present in residential solar systems of different capacity by assuming and modeling a base-line case of an installation of 6,2 kW with the features that are presented in *Table 12*.

Table 12. Residential PV: Modeling Inputs and Assumptions.

Category	Modeled Value	Description	Sources
System size	6.2 kW	Average installed size per system	Go Solar CA (2018)
Module efficiency	17.2%	Average module efficiency	Go Solar CA (2018)
Module price	$0.47/Wdc	Ex-factory gate (first buyer) price, Tier 1 modules	GTM and SEIA (2018), NREL (2018)
Inverter price	Single-phase string inverter: $0.12/Wdc DC power optimizer string inverter: $0.18/Wdc Microinverter: $0.39/Wdc	Ex-factory gate (first buyer) prices, Tier 1 inverters	PVinsights (2018), NREL (2018), corporate filings (Enphase 2018, SolarEdge 2018)
Structural BOS (racking)	$0.10/Wdc	Includes flashing for roof penetrations and all the rails and clamps	NREL (2018)
Electrical BOS	$0.19–$0.27/Wdc Varies by inverter option	Conductors, switches, combiners and transition boxes, as well as conduit, grounding equipment, monitoring system or production meters, fuses, and breakers	Model assumptions, NREL (2018), RSMeans (2017)
Supply chain costs (% of equipment costs)	Varies by installer type	15% costs and fees associated with shipping and handling of equipment multiplied by the cost of doing business index (101%) Additional 35% small-scale procurement for module-related supply chain costs for small installers. Additional 20% for inverter-related supply chain costs for small installers and 10% for national integrators	NREL (2018), model assumptions
Sales tax	Varies by location; weighted national average: 6.9%	Sales tax on the equipment; national benchmark applies an average (by state) weighted by 2017 installed capacities	RSMeans (2018), GTM and SEIA (2018)
Direct installation labor	Electrician: $19.74–$38.96 per hour; Laborer: $12.88–$25.57 per hour; Varies by location and inverter option	Modeled labor rate depends on state; national benchmark uses weighted average of state rates	BLS (2018), NREL (2018)
Burden rates (% of direct labor)	Total nationwide average: 31.8%	Workers compensation (state-weighted average), federal and state unemployment insurance, Federal Insurance Contributions Act (FICA), builders risk, public liability	RSMeans (2018)
Permitting, inspection, and interconnection (PII)	$0.06/Wdc	Includes assumed building permitting fee of $200 and six office staff hours for building permit preparation and submission, and interconnection application preparation and submission	NREL (2018)
Sales & marketing (customer acquisition)	$0.30/Wdc (installer) $0.44/Wdc (integrator)	Total cost of sales and marketing activities over the last year—including marketing and advertising, sales calls, site visits, bid preparation, and contract negotiation; adjusted based on state "cost of doing business" index	NREL (2017), Sunrun (2017), Vivint Solar (2017), Feldman et al. (2013)
Overhead (general & administrative)	$0.29/Wdc (installer) $0.37/Wdc (integrator)	General and administrative expenses—including fixed overhead expenses covering payroll (excluding permitting payroll), facilities, administrative, finance, legal, information technology, and other corporate functions as well as office expenses; adjusted based on state "cost of doing business" index	NREL (2018), Feldman et al. (2013)
Profit (%)	17%	Fixed percentage margin applied to all direct costs including hardware, installation labor, direct sales and marketing, design, installation, and permitting fees	Fu et al. (2017)

Note: Reprinted from U.S. Photovoltaic System Cost Benchmark: Q1 2018 (pg 17) by NREL, 2018.

Considering these considerations, different cases are presented with the decomposition of the total costs, as *Figure 67* illustrates. In such figure it can be observed that the price for the modules remains constant and few variations are noticeable among the different cases besides the case of the use of microinverters, which seems to be a bit more expensive than the other cases, resulting in a weighted average of 2,70 USD/Wdc.

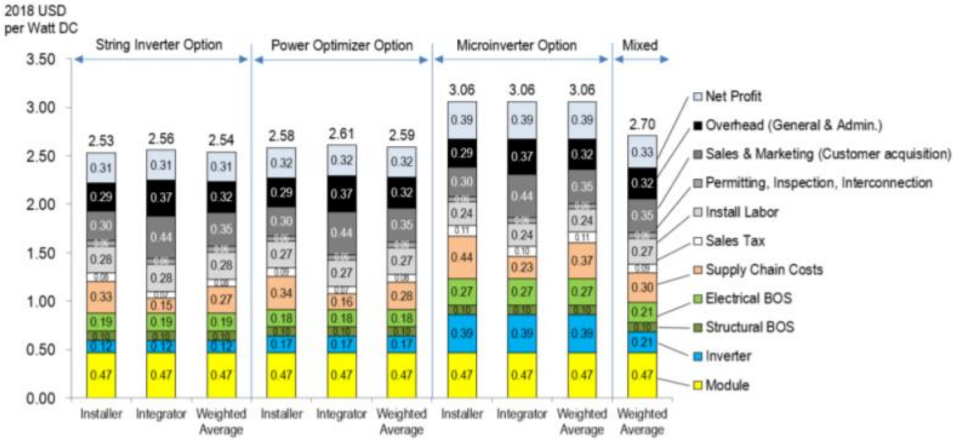


Figure 67. Q1 2018 U.S. benchmark: 6.2 kW residential system cost (2018 USD/Wdc). Reprinted from U.S. Photovoltaic System Cost Benchmark: Q1 2018 (pg 18) by NREL, 2018

Moreover, the reduction trend that it is experiencing this sector since 2010 until 2018 is also demonstrated. In this case the cost per unit of power installed seems to be quite higher than the other two cases studied of commercial and utility-scale. Considering that the commercial sector also has a higher cost per Watt, it can be concluded that the costs regarding a PV system seems to decrease while increasing its capacity.

In *Figure 68* it can be noticed an important decrease of the costs of residential PV systems as NREL states, it has been reduced a 63% since 2010. Again, the most important factor driving such reduction is attributed to the hardware costs (module, inverter and hardware BOS) responsible for 57% of such drop. Approximately 19% is due to the labor reduction costs and the final 24% comes from the soft cost reductions.

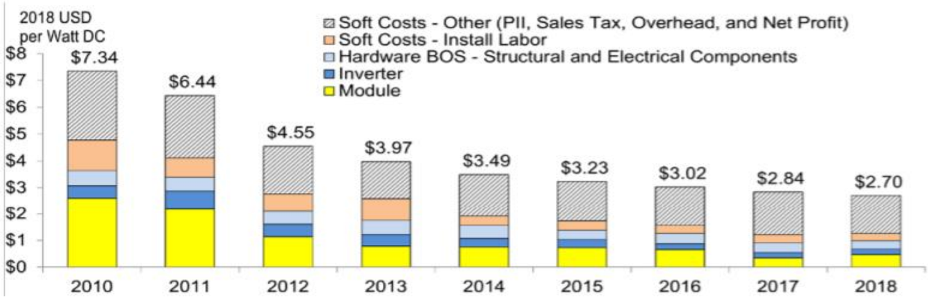


Figure 68. NREL residential PV system cost benchmark summary, 2010-2018. Reprinted from U.S. Photovoltaic System Cost Benchmark: Q1 2018 (pg 21) by NREL, 2018

Furthermore, NREL predicts such prices to reduce even more for the 2030. In the *figure 69* it is presented two different scenarios (visionary and less aggressive) in which it is predicted the cost reduction for PV systems either for new constructions or roof replacement.

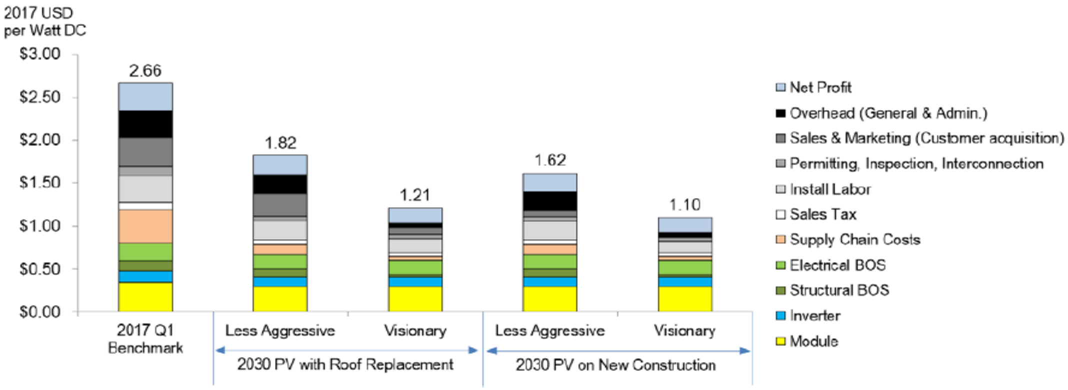


Figure 69. Modeled installed residential PV system prices at time of roof replacement and new construction in 2030, compared with a weighted average of the Q1 2017 benchmark. Reprinted from Cost-Reduction Roadmap for Residential Solar Photovoltaics (PV), 2017-2030

In this topic, *Solar Choice* database allows to analyze the prices regarding the residential PV systems in Australia for installations ranging from 1.5 kW to 10 kW. As *figure 70* indicates, the trend for the residential systems in Australia is also to decrease considerably, even though there can appear some seasonal variations, especially for the smaller systems. *Solar Choice* makes surveys to installers and manufacturers in Australia and then analyses the evolution of the price in residential and commercial systems. For this project, both residential and commercial systems have been analyzed.

The structure of the Solar PV systems in Australia is complex since it is a *Feed-in* system, subsidies from the government. The incentive, known as STC certificate, the owner of the residential system receives from the government depends basically on the final output of the solar system to be installed. At the same time, this system depends on the type of generation unit, the location where it is placed, the year you install it and the size. Based on that, you receive subsidy according to the price that is being paid in that moment for the STC’s (which are kind of a currency), which is highly variable. This STC’s methodology applies both for the residential and for commercial systems, shown previously. (Australian Government, 2018). Within the cities shown in *Solar Choice* database prices in Australia, the cheapest place is Perth, since it has high rates of irradiance. The only drawback that must be considered when using the data prices from *Solar Choice* is that a 30% discount is applied, which is approximately the subsidy each owner receives (Solar Choice, 2019). In the IEA PVPS Annual Report 2018, this discount rate is also revealed in the page 43, when it gives the residential system average price value with and without subsidy, being the difference approximately 30%, which backups the information obtained in (Solar Choice, 2019). (IEA PVPS, 2018)

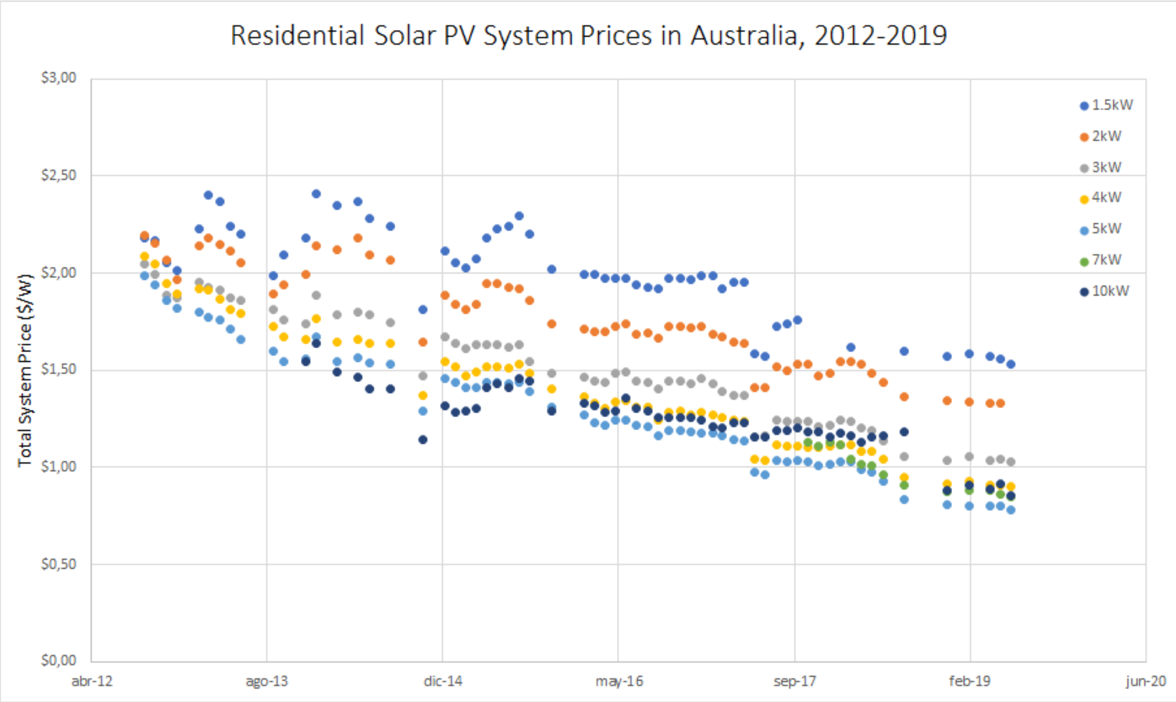


Figure 70. Residential Solar PV System Prices in Australia, 2012-2019. Own creation based on data from Solar Choice, 2019.

On the other hand, it is worth looking to the case of Germany, which has been a top-world leader in the solar field development (IRENA, 2018, pág. 71), not just because has invested on the maturing of that technology but for the subsidies schemes that the government has designed to promote the use of this renewable resource. As *Figure 71* shows (Fraunhofer ISE, 2019), since 1990 there have been several initiatives and programs developed, uninterruptedly, to encourage the investment in solar power. This has helped enormously to decrease the costs of a residential rooftop-system, up to 10kWp. As it is shown, since that moment there has been an important reduction on the costs, also helped due to the increase of the installed capacity and the introduction of the feed-in tariff programs.

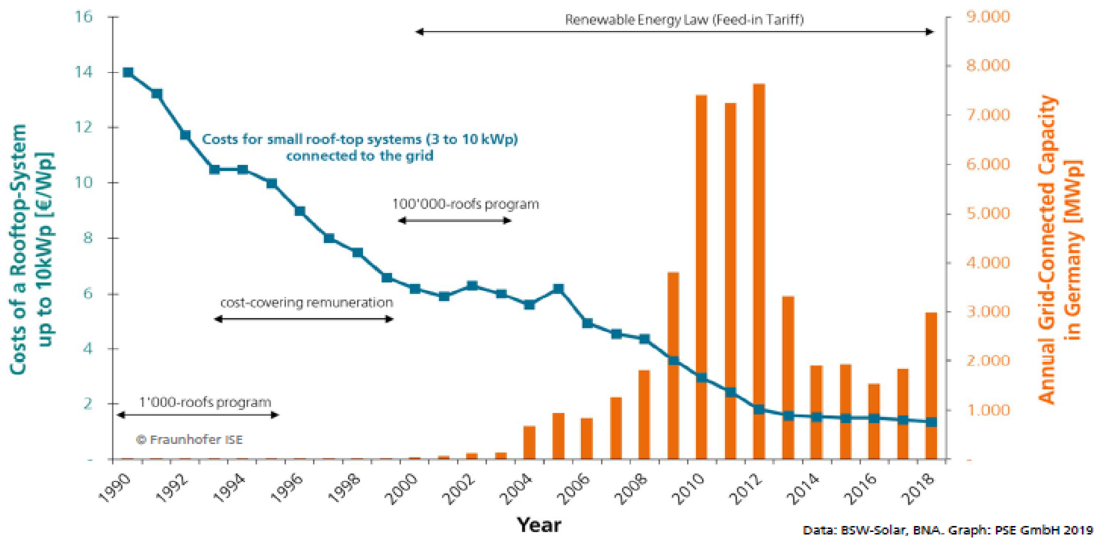


Figure 71. Investment for Small Rooftop PV systems in relation to Market Development and Subsidy Schemes in Germany. Reprinted from Photovoltaics Report (pg 41) by Fraunhofer, 2019

In the same report (Fraunhofer ISE, 2019), it is highlighted that in the last decade (2008-2018), the influence of the solar modules cost on the total cost of an average PV Rooftop System (10 kWp - 100 kWp) has decreased drastically, *Figure 72*. If in 2008 the percentage was 74%, in 2018 went down to 45%. The contrary happened with the Balance of the System, inverter included, that went from 26% to 55% (Fraunhofer ISE, 2019).

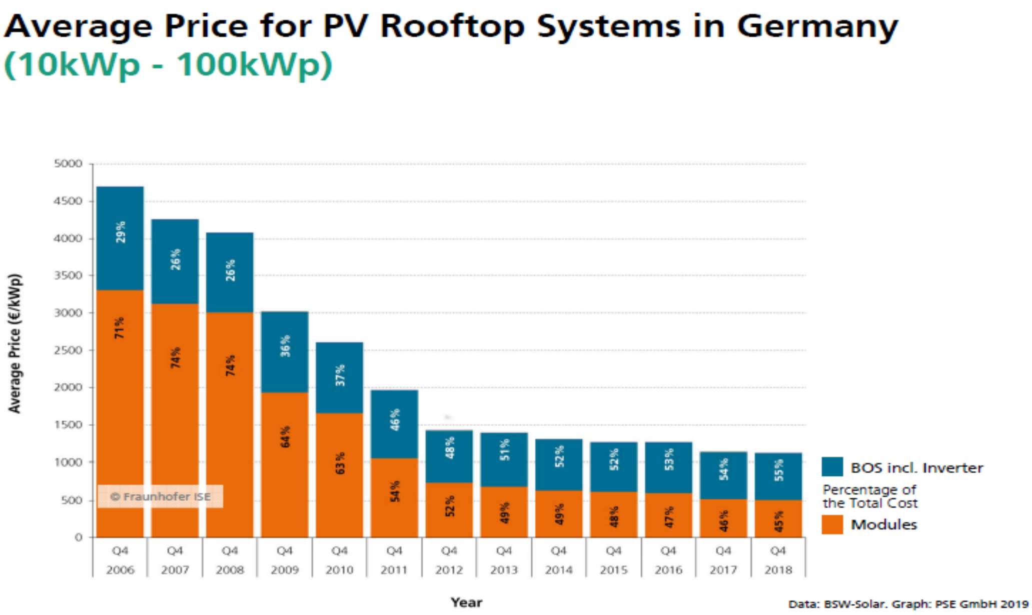


Figure 72. Average Price for PV Rooftop Systems in Germany (10 kWp - 100 kWp). Reprinted from Photovoltaics Report (pg 42) by Fraunhofer, 2019.

2.6.4. Real examples of cost breakdown for different size projects in various locations

The difficulties faced by the authors in order to find public information regarding project costs has been one of the main problems during the writing of this project. The biggest source of detailed information in this aspect has been obtained from *National Renewable Energy Laboratory (NREL),* an American government owned organization depending from the United States Department of Energy (Wikipedia, 2019) and dedicated towards research, development, commercialization and deployment of renewable energy and energy efficiency technologies. However, few costs breakdown have been found in different countries apart from the ones from *NREL*. The idea of this section is to present three projects that have publicly posted its cost breakdown. The aim is to see if what is found agrees with the investigations made until this point: how is the breakdown structured, which part has the most influence in the final price, if the soft costs are included or otherwise, they are not considered.

The first one is a commercial system of 1 MW located in Turkey, obtained from (Gürtürk, 2019, pág. 868). In fact, in this case is a quite precise estimation of how a breakdown in a system of this time in Elazig is, in Turkey. In *Table 13* the cost breakdown is presented.

Table 13. Cost breakdown of a commercial system of 1 MW in Turkey

Cost parameters breakdown of a 1 MW power plant in Turkey			
Parameter	***Cost (US$)***	***Share***	***Cost per Watt***
PV Modules (270 W)	594.000,00 US$	51,35%	0,59 US$
Inverter	98.600,00 US$	8,52%	0,10 US$
Construction	78.078,00 US$	6,75%	0,08 US$
Transformer kiosk	12.253,00 US$	1,06%	0,01 US$
Distributing center	7.840,00 US$	0,68%	0,01 US$
DC cable	9.744,00 US$	0,84%	0,01 US$
AC cable	19.302,00 US$	1,67%	0,02 US$
SCADA	9.500,00 US$	0,82%	0,01 US$
Transformer	12.000,00 US$	1,04%	0,01 US$
Earthing	14.575,00 US$	1,26%	0,01 US$
Board packages	24.464,00 US$	2,11%	0,02 US$
Wire fence	5.413,00 US$	0,47%	0,01 US$
Camera and digital video recorder	7.287,00 US$	0,63%	0,01 US$
External lightning protection earth	6.038,00 US$	0,52%	0,01 US$
Panel mounting	11.556,00 US$	1,00%	0,01 US$
Construction mounting	16.553,00 US$	1,43%	0,02 US$
Area excavation	3.123,00 US$	0,27%	0,00 US$
Turkey Eelctricity Distribution Company (TEDAS) project	6.246,00 US$	0,54%	0,01 US$
Transport	7.079,00 US$	0,61%	0,01 US$
Financing cost	16.657,00 US$	1,44%	0,02 US$
Unexpected expenses and others	20.000,00 US$	1,73%	0,02 US$
Total (without value-added tax (18%))	980.308,00 US$	84,75%	0,98 US$
TOTAL COST with tax (18%)	***1.156.763,00 US$***	***100,00%***	***1,16 US$***

Note: Own creation based on data from Economical feasibility of solar power plants based on PV module with levelized cost analysis. Energy. 2019. pg 868.

The breakdown is explicit and detailed, however, at first sight there is no explicit mention on how much are the soft-costs accounting for the project. Indeed, this is one of the big unknowns while doing the project, to know why they are usually not properly detailed or disclosed. As expected, the cost of the PV Modules is the greatest, accounting for more than half of the total cost share. In addition, the price of them is high in comparison to what has been studied. Interesting to mention the low cost that the inverter has, accounting 0.10 USS/W and being slightly low in comparison with the ones shown in the section *1.3.2) Inverters* from this project. It accounts for 8% of the total share. The overall cost of the project is 1.16 USD/W, lower than the one posted by *NREL* (1,72USD/W for a system of 1 MW) (Fu, Feldman, & Margolis, 2018), so in fact, this looks like a decent project.

The next two projects presented are placed in China. The information regarding their costs was found in the *National Survey Report of PV Power Applications in China* by *IEA, 2016* (Fang, Honghua, & Sicheng, 2016). Since the values given in the report where in Yuan, what has been done is to apply a money change to USD, which has been the following: *1 yuan = 0.14549 USD* revised on July 10th, 2019. The projects shown are dated from 2016, so they might be a bit out-of-time and value may differ from what is being paid right now, since Solar PV technology is continuously changing, improving and lowering its prices. In *Table 14* and *Table 15* the values of the breakdown are shown.

Table 14. Commercial scale (1 MW) Solar PV system cost breakdown in USD/W

	Commercial Scale (USD/W)					
	Cost Breakdown for a 1MW Building PV system					
	Item	Equipment	Installation	Others	Total	Share
A	**Equipment and Installation**	654.727,50 USD	39.283,65 USD		694.011,15 USD	**66,10%**
1	PV Modules	494.683,00 USD	23.279,20 USD		517.962,20 USD	49,34%
2	Inverters	72.747,50 USD	7.274,75 USD		80.022,25 USD	7,62%
3	Monitoring and Control Equipment	43.648,50 USD	4.364,85 USD		48.013,35 USD	4,57%
4	Other Equipment	43.648,50 USD	4,36 USD		48.013,35 USD	4,57%
B	**Construction**	145.495,00 USD	116.396,00 USD		261.891,00 USD	**24,95%**
1	Roof Pre-Treatment	0,00 USD	14.549,50 USD		14.549,50 USD	1,39%
2	Supporting Structure	72.747,50 USD	14.549,50 USD		87.297,00 USD	8,32%
3	Cable and Installation	72.747,50 USD	14.549,50 USD		87.297,00 USD	8,32%
4	Grid Connection	0,00 USD	29.099,00 USD		29.099,00 USD	2,77%
5	Transport and Warehouse	0,00 USD	43.648,50 USD		43.648,50 USD	4,16%
C	**Others**			72.747,50 USD	72.747,50 USD	**6,93%**
1	Survey and Design			43.648,50 USD	43.648,50 USD	4,16%
2	Management			29.099,00 USD	29.099,00 USD	2,77%
	A-C Total	800.222,50 USD	155.679,65 USD	72.747,50 USD	1.028.649,65 USD	97,99%
	Budget Reserve				21.824,25 USD	2,01%
	Static Investment	USD			1.057.748,65 USD	100,00%
	Unit Static Investment	USD/W			1,05774865	

Note:Own creation using data from Lv Fang, Xu Honghua, Wang Sicheng. National Survey Report of PV Power Applications in China, 2016. IEA (International Energy Agency). pg 7

Although it is detailed, in the case of the Equipment and Installation, it does not account the soft-costs of the project. As it happened in the previous project (Gürtürk, 2019), in Turkey, the PV Modules share is the biggest, accounting for almost half of the total share, which indeed was expected. Moreover, the influence on the final price of the Inverter is the same as it was in the Turkish example. The final price of the project is 1.06 USD/W.

Table 15. Utility-scale (10 MW) Solar PV system cost breakdown in USD/W

	Utility Scale System in China					
	Cost Breakdown for a 10MW System					
	Item	***Equipment***	***Installation***	***Others***	***Total***	***Share***
A	***Equipment and installation***	6.590.923,50 USD	407.386,00 USD		6.998.309,50 USD	***66,80%***
1	PV Modules	4.655.840,00 USD	218.242,50 USD		4.874.082,50 USD	47,88%
2	Inverters	509.232,50 USD	29.099,00 USD		538.331,50 USD	5,29%
3	Supporting Structure	581.980,00 USD	72.747,50 USD		654.727,50 USD	6,43%
4	Transformers	290.990,00 USD	29.099,00 USD		320.089,00 USD	3,14%
5	Monitoring and Control Equipment	407.386,00 USD	43.648,50 USD		451.034,50 USD	4,43%
6	Other Equipment	145.495,00 USD	14.549,50 USD		160.044,50 USD	1,57%
B	***Construction***	***960.267,00 USD***	***1.484.049,00 USD***		***2.444.316,00 USD***	***23,33%***
1	Foundation		436.485,00 USD		436.485,00 USD	4,29%
2	Cable and Installation	552.881,00 USD	145.495,00 USD		698.376,00 USD	6,86%
3	Housing Construction	0,00 USD	436.485,00 USD		436.485,00 USD	4,29%
4	Transformer Station	407.386,00 USD	72.747,50 USD		48.013,35 USD	4,72%
5	Transport and Warehouse	0,00 USD	218.242,50 USD		218.242,50 USD	2,14%
6	Auxiliary Engineering	0,00 USD	174.594,00 USD		174.594,00 USD	1,71%
C	***Others***			***82.786,66 USD***	***827.866,55 USD***	***7,90%***
1	Land for Housing			8.729,70 USD	87.297,00 USD	0,86%
2	Management			40.593,11 USD	405.931,05 USD	3,99%
3	Pre-Conditioning			11.639,60 USD	116.396,00 USD	1,14%
4	System Design			21.824,25 USD	218.242,50 USD	2,14%
	A-C total	7.551.190,50 USD	1.300,00 USD	569,00 USD	10.270.492,05 USD	98,04%
	Budget Reserve	2%			205.409,84 USD	1,96%
	Statis Investment	USD			10.475.901,89 USD	100,00%
	Active Investment	Including Interest during installation				
	Unit Static Investment	(USD/W)			1,047590189	

*Note**:** Own creation using data from Lv Fang, Xu Honghua, Wang Sicheng. National Survey Report of PV Power Applications in China, 2016. IEA (International Energy Agency). pg 7,8*

The next one is a utility scale project with 10 MW (*Table 15*) also in China (Fang, Honghua, & Sicheng, 2016), and it has quite the same structure as the commercial one (1 MW). It could be expected that there is an economy of scale in the prices, but in this case, there is not a high reduction in that sense. Still, the total share of the PV modules drops a bit, but not remarkably.

In conclusion, it has been difficult to find a deep disclosure regarding the system costs associated to a Solar PV project. Although there is concordance with the installations and equipment, there is a lack of information regarding what include the soft-costs in the project, which in fact are becoming more important as the other costs are constantly being reduced. The lack of public cost breakdown information is mainly because it is a competitive market and it is preferable not to make public such kind of information.

2.7. Solar PV Project Costs for different Countries and systems

The cost trends of a PV system have been explained previously in a global term, however, such costs are very variable depending on the country in which the PV project is carried out. Thus, is necessary to discretize in order to discover which are the most advanced countries in this technology sector.

As it explained in IRENA's report, *Renewable Power Generation Costs in 2018* (IRENA, 2019), thanks to *Figure 73*, there are some countries which have been leading the development of such technology and have reduced its costs more than other countries. This is the case of China, Italy and India, which in 2018 had the lowest cost per installed system, in the utility-scale perspective, reaching prices below 1 $/W.

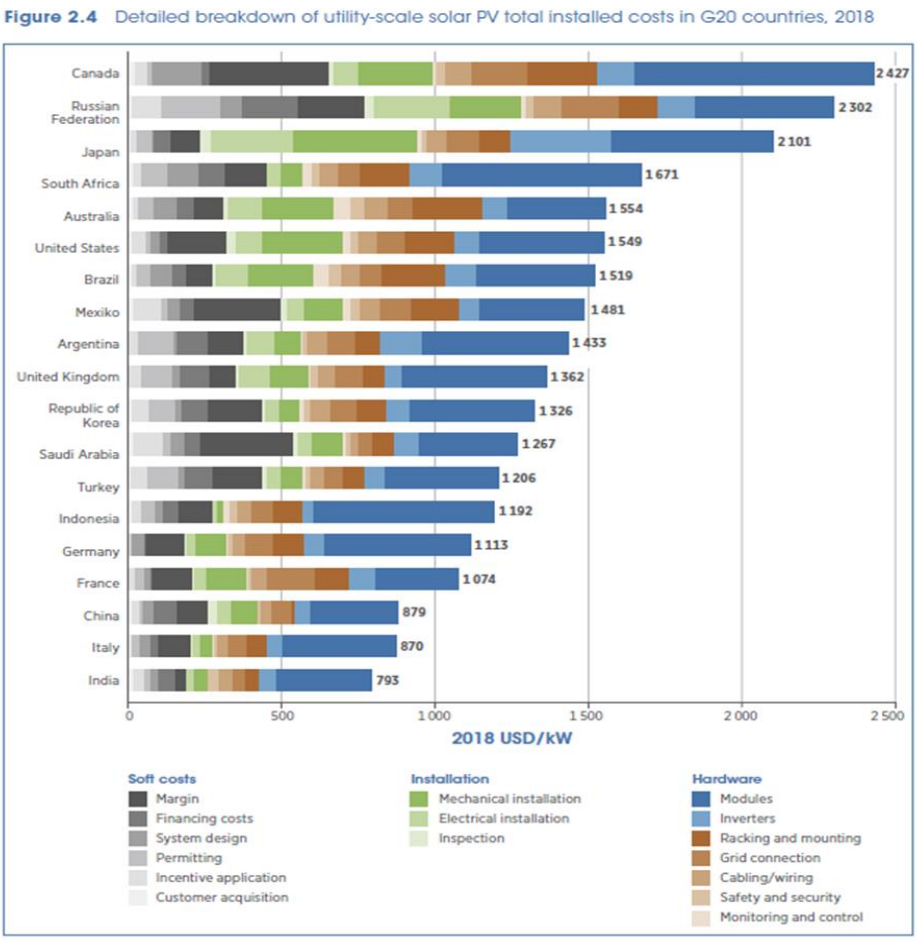


Figure 73. Detailed breakdown of utility-scale solar PV total installed costs in G20 countries. Reprinted from Renewable Power Generation Costs in 2018 (pg 46) by IRENA, 2019

In more detail, such graphic is divided on the three big main concepts: Soft Costs, Installation Costs and Hardware Costs, helping to understand how the cost are distributed depending on the country. In this case it is only done for ten out the twenty countries that appear in the *Figure 73.*

Firstly, we find the Soft Costs (*Figure 74*), which are basically increased by the margin of benefit, accounting for about 50% of the total Soft Costs in most of the cases except for India, which is more influenced by the Financing Costs.

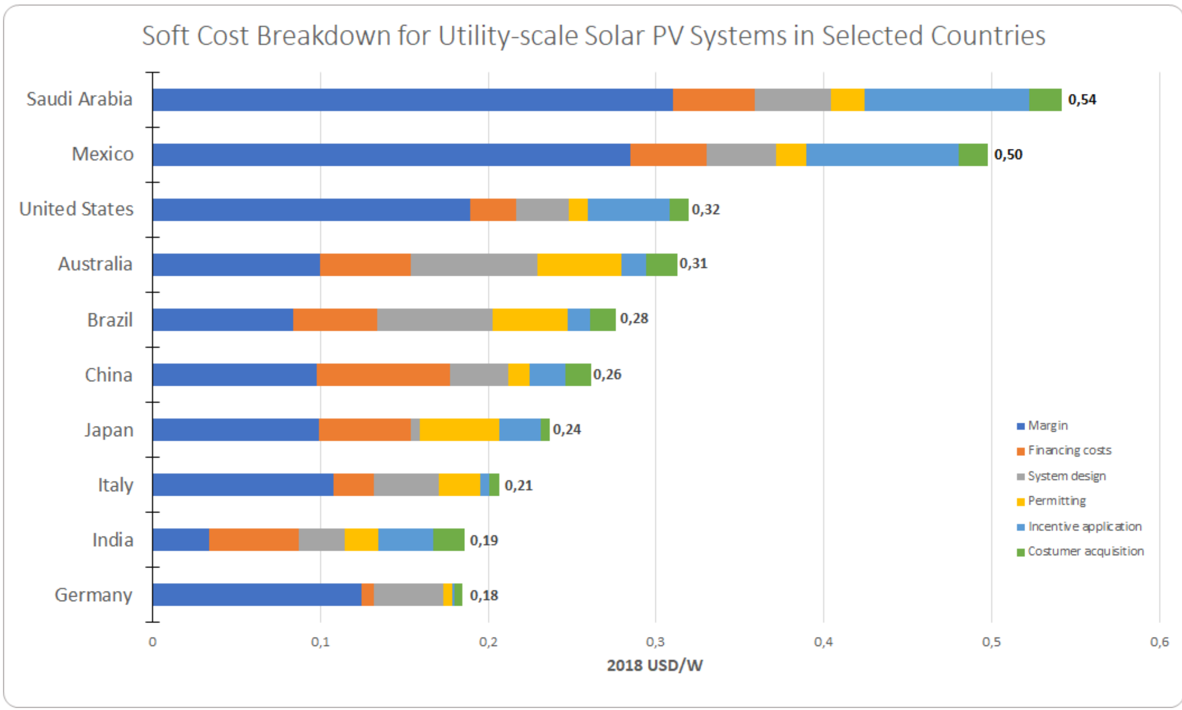


Figure 74. Soft Cost Breakdown for Utility-scale Solar PV Systems. Own creation based on IRENA 2019 database, 2019

Consequently, it is studied the Installation Costs (*Figure 75*). For the installation costs, most of them come from the mechanical installation, being the electrical installation less expensive besides the case of Japan, which shows a high cost for both mechanical and electrical installation.

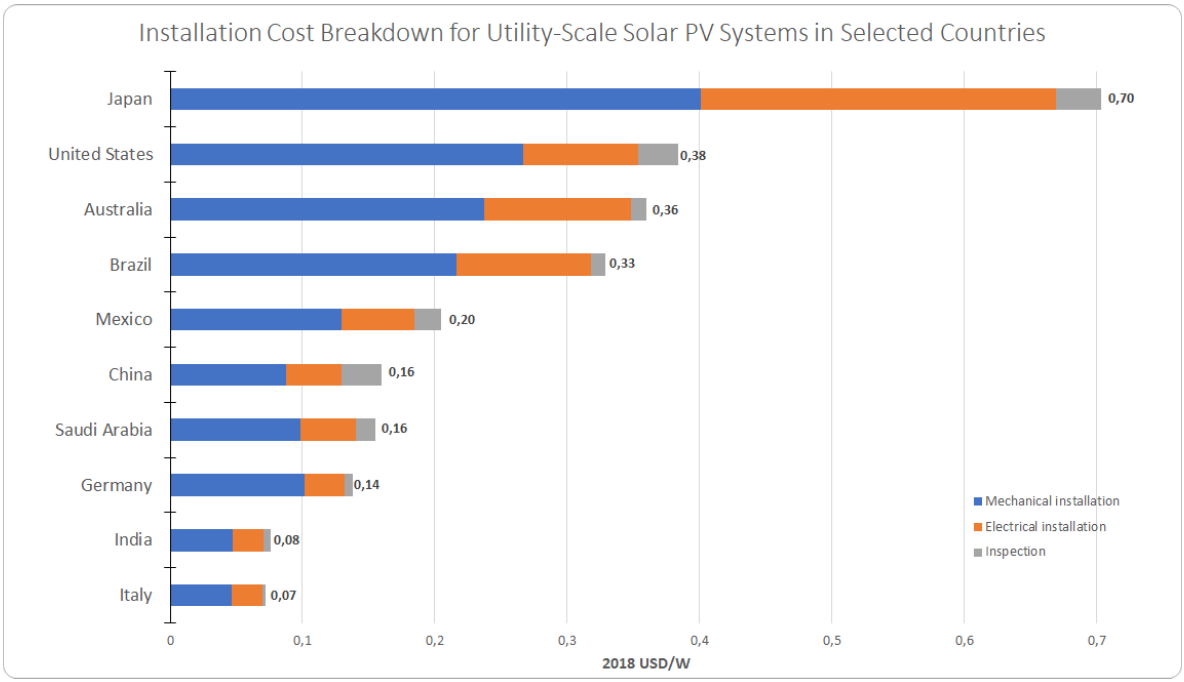


Figure 75. Installation Cost Breakdown for Utility-scale Solar PV Systems. Own creation based on IRENA 2019 database

Finally, it is presented the cost breakdown regarding the Hardware technology (*Figure 76*), which allows to confirm that the most expensive hardware component is the module, accounting for more than half of the total costs in most of the countries. Meanwhile, the Racking and Mounting Costs seem to be kind of variable depending on the country, being the differential component for the cheapest countries.

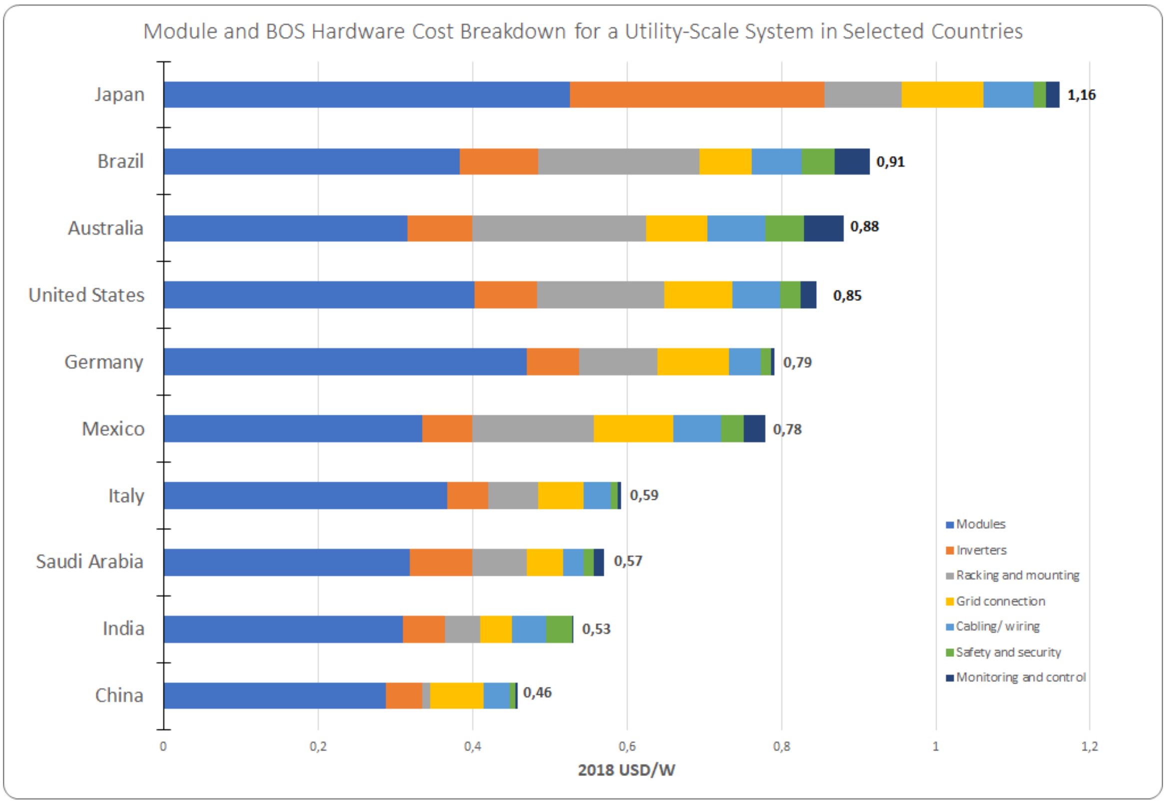


Figure 76. Module and BOS Hardware Cost Breakdown for Utility-scale Solar PV Systems. Own creation based on IRENA 2019 database.

To understand how such prices have been reached is important to consider the historical prices trend, plotted in *Figure 77*. Such figure shows the price reduction in some of the most developed counties, from 2010 to 2018. From that figure is remarkable the fact that countries like Germany and the US, which are known for being so well developed, have experienced low cost reduction compared to countries like India and Italy, which reduced the costs an 84% and 83% respectively in the frame time considered. (IRENA, 2019)

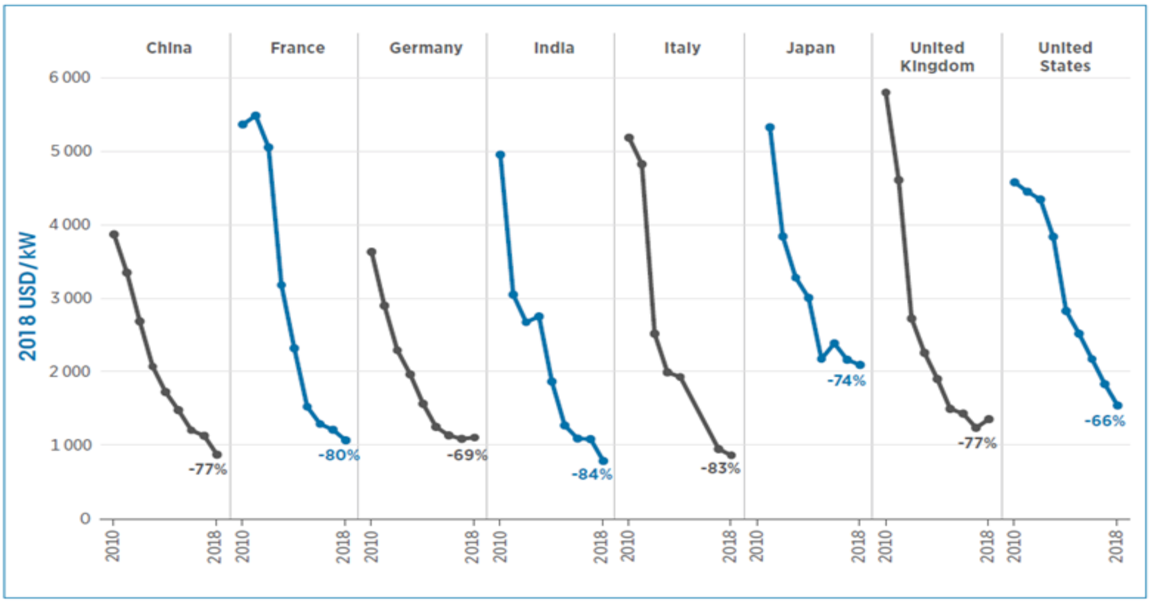


Figure 77. Utility-scale solar PV total installed cost trends in selected countries, 2010-2018. Reprinted from Renewable Power Generation Costs in 2018 (pg 45) by IRENA, 2019.

On the other hand, for the residential case, (IRENA, 2015) also presented its price evolution from 2006 to 2014, in *Figure 78*, where Germany and China appeared as the leading countries, having the cheapest prices per kilowatt for a PV installation. As it can also be observed, even though all the countries are advancing with a similar trend, Germany and China have been the countries with the cheapest costs, with a value a bit over the 2000 $/kW.

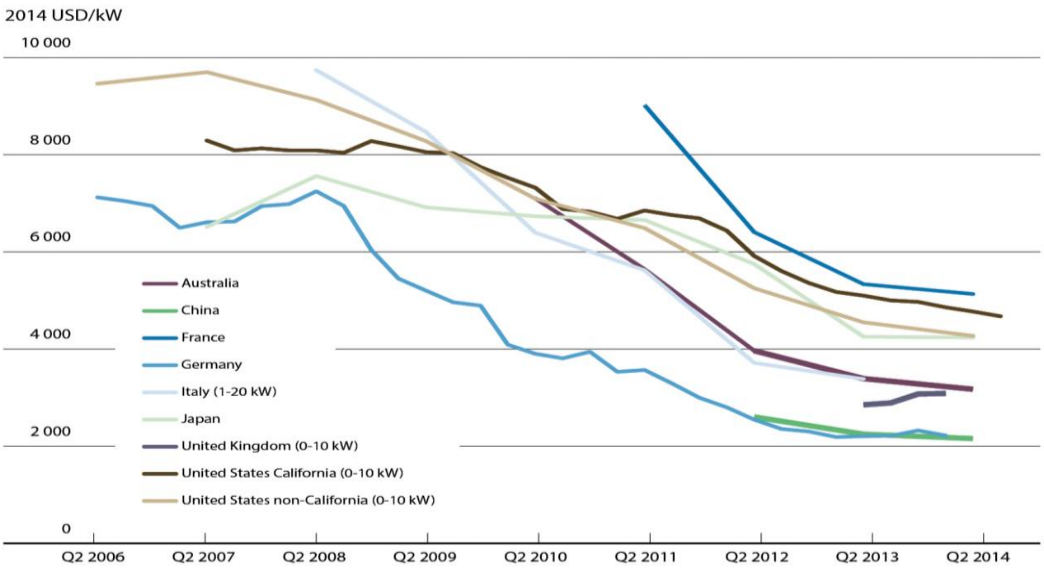


Figure 78. Average Total Installed Cost of Residential Solar PV Systems by Country, 2006-2014. Reprinted from Renewable Power Generation Costs in 2014 (pg 88) by IRENA, 2015.

Summarizing all the types of installation costs for the different countries, IEA presents a table in the report *Trends 2018 in Photovoltaic Applications* (IEA PVPS, 2018) (*Table 16*), in which it is detailed the indicative price per installed system for selected countries and in 2017. This table allows to determine and confirm that China is the country with the cheapest costs for most types of installation (highlighted in green), meanwhile, Japan appears to be the one with most of the more expensive systems (highlighted in red).

Table 16. Indicative Installed System Prices in Selected IEA PVPS Reporting Countries in 2017.

	GRID-CONNECTED (LOCAL CURRENCY OR USD PER W)								OFF-GRID (LOCAL CURRENCY OR USD PER W)			
	RESIDENTIAL		COMMERCIAL		INDUSTRIAL		GROUND-MOUNTED		<1 kW		>1 kW	
COUNTRY	LOCAL CURRENCY/W	USD/W	LOCAL CURRENCY/W	USD/W	LOCAL CURRENCY/W	USD/W	LOCAL CURRENCY/W	USD/W	LOCAL CURRENCY/W	USD/W	LOCAL CURRENCY/W	USD/W
AUSTRALIA	2,22	1,63	2,01	1,48	NA	NA	2,24	1,65	NA	NA	NA	NA
AUSTRIA	1,62	1,76	1,19	1,29	NA	NA	NA	NA	5,00	5,42	NA	NA
BELGIUM	1,2 - 1,7	1,3 - 1,84	1,1 - 1,2	1,19 - 1,3	0,85 - 1,1	0,92 - 1,19	NA	NA	NA	NA	NA	NA
CANADA	2,5 - 3,2	1,85 - 2,37	2 - 2,5	1,48 - 1,85	1,8 - 2	1,33 - 1,48	1,80	1,33	NA	NA	NA	NA
CHINA	5,5 - 6	0,78 - 0,85	5,5 - 6	0,78 - 0,85	5,5 - 6	0,78 - 0,85	5 - 5,5	0,71 - 0,78	NA	NA	NA	NA
DENMARK	7 - 13	1,02 - 1,89	6 - 12	0,87 - 1,75	6 - 13	0,87 - 1,89	3 - 7	0,44 - 1,02	8 - 22	1,17 - 3,21	NA	NA
FRANCE	1,9 - 2,6	2,06 - 2,82	1,20	1,30	0,90	0,98	0,8 - 1	0,87 - 1,08	NA	NA	NA	NA
FINLAND	1,2 - 1,8	1,3 - 1,95	0,9 - 1,15	0,98 - 1,25	0,85 - 1,15	0,92 - 1,25	0,9 - 1,1	0,98 - 1,19	5,00	5,42	NA	NA
GERMANY	1,13 - 1,58	1,22 - 1,71	0,85 - 1,35	0,92 - 1,46	0,98	1,06	0,92	0,99	NA	NA	NA	NA
ISRAEL	5 - 6	1,33 - 1,6	3,5 - 3,8	0,93 - 1,01	3 - 3,2	0,8 - 0,85	2,6 - 2,77	0,69 - 0,74	NA	NA	NA	NA
ITALY	1,2 - 1,6	1,3 - 1,73	1 - 1,4	1,08 - 1,52	0,8 - 1	0,87 - 1,08	0,7 - 0,9	0,76 - 0,98	NA	NA	NA	NA
JAPAN	277,00	2,37	244,00	2,09	244,00	2,09	221,00	1,89	NA	NA	NA	NA
KOREA	1 500 - 2 000	1,27 - 1,7	2 200 - 2 300	1,87 - 1,95	NA	NA	1 400 - 2 000	1,19 - 1,7	NA	NA	NA	NA
MALAYSIA	5,5 - 6	1,33 - 1,45	4,5 - 5,5	1,09 - 1,33	3,7 - 4,5	0,89 - 1,09	3,5 - 4,4	0,84 - 1,06	7,5 - 8	1,81 - 1,93	25 - 35	6,03 - 8,45
PORTUGAL	1,40	1,52	1,20	1,30	1,00	1,08	0,6 - 0,8	0,65 - 0,87	2,00	2,17	1,60	1,73
SPAIN	1,4 - 1,5	1,52 - 1,63	0,8 - 1,2	0,87 - 1,3	NA	NA	0,88	0,95	2,5 - 3	2,71 - 3,25	NA	NA
SWEDEN	14,80	1,66	12,20	1,37	10,70	1,20	9,30	1,05	25,00	2,81	20,00	2,25
SWITZERLAND	2,2 - 4	2,15 - 3,91	1,1 - 2,5	1,07 - 2,44	0,9 - 1,5	0,88 - 1,46	NA	NA	10 - 15	9,77 - 14,65	8 - 7	7,81 - 6,84
USA	2,88	2,88	1,55	1,55	NA	NA	0,98	0,98	NA	NA	NA	NA

NOTE: DATA REPORTED IN THIS TABLE DO NOT INCLUDE VAT.

SOURCE IEA PVPS.

Note: Reprinted from Trends 2018 in Photovoltaic Applications (pg 70) by IEA, 2018.

The cost reduction of this sector in each of these countries, has been led mainly by the fact that the module costs have been, as well, reduced impressively in each of them. As it has been presented in previous sections (*Figure 27* and *28*), module prices are particularly cheap in countries like China and Germany, due to its enormous production, meanwhile Japan remains as one of the most expensive countries in that matter.

Following, module prices from 2018 in selected countries are presented in *Table 17*, from the IEA report, *Trends 2018 in photovoltaic applications* (IEA PVPS, 2018), where it is demonstrated the prices per unit of power of the modules in the most important countries in this sector. Such table indicates that the lowest prices are reached in the countries highlighted in green: Israel, Malaysia and Portugal, but most of the countries seems to be close to their prices of around 0.3 USD/W, meanwhile Japan seems to be way far to reach such prices.

Table 17. Indicative Module Prices in Selected Reporting Countries.

COUNTRY	CURRENCY	LOCAL CURRENCY/W	USD/W
AUSTRALIA	AUD	0,53 - 1,35	0,4 - 1
AUSTRIA	EUR	0,38 - 0,63	0,4 - 0,7
BELGIUM	EUR	0,35 - 0,5	0,4 - 0,5
CANADA	CAD	0,75 - 0,81	0,6 - 0,6
CHINA	CNY	3	0,4
DENMARK	DKK	2 - 4	0,3 - 0,6
FINLAND	EUR	0,4 - 0,55	0,4 - 0,6
GERMANY	EUR	0,38 - 0,5	0,4 - 0,5
ISRAEL	ILS	1,30	0,3
ITALY	EUR	0,32 - 0,56	0,3 - 0,6
JAPAN	JPY	131	1,12
KOREA	KRW	456 - 646	0,4 - 0,5
MALAYSIA	MYR	1,34 - 1,54	0,3 - 0,4
PORTUGAL	EUR	0,3 - 0,6	0,3 - 0,7
SPAIN	EUR	0,45 - 0,64	0,5 - 0,7
SWEDEN	SEK	4,1 - 6,6	0,5 - 0,7
USA	USD	0,39	0,39

NOTES: DATA REPORTED IN THIS TABLE DO NOT INCLUDE VAT.
GREEN = LOWEST PRICE. RED = HIGHEST PRICE.

Note: Reprinted from Trends 2018 in Photovoltaic Applications (pg 70) by IEA, 2018.

The LCOE derived from all the costs accounted, is also presented in a timeline frame in *Figure 79*. This figure shows the evolution and reduction of the LCOE for all the countries from 2014 until 2018 while indicates the most expensive and cheapest country of each of the quarters of the year. It can be noticed that over the years the cost range is getting narrower meaning that standardization is being reached and cost are becoming more similar all over the world; also, it can be detected the global decreasing trend which seems to slow down for the last period. (IEA PVPS, 2018)

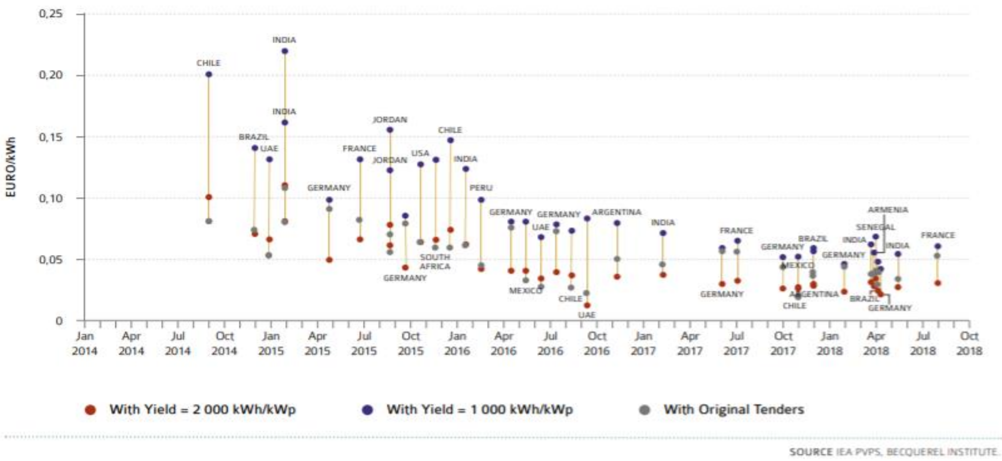


Figure 79. Normalized LCOE for Solar PV based on Recent PPA Prices 2014 - Q2 2018. Reprinted from Trends 2018 in Photovoltaic Applications (pg 46) by IEA, 2018.

In more general approach, IRENA demonstrate the LCOE in 2015 by region in the world in the report *Renewable Power Generation Costs in 2015*, where it is classified the weighted average LCOE in the different main regions. As it can be observed in *Figure 80*, lowest prices are reached in Central America, the Caribbean and South America, thanks to the greater radiation in this zone, with prices below 0.1 USD/kWh in 2015. Also, there appear how cheap is energy production in Asia, North America and Europe, being Europe the country with less variability thanks to the spread standardization in this country.

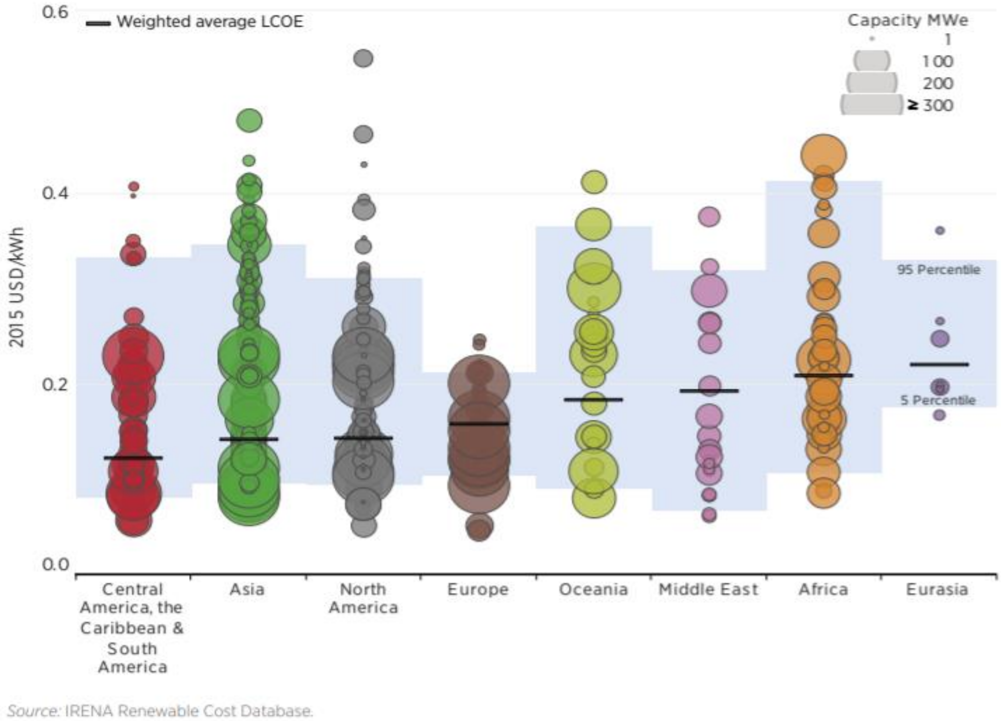


Figure 80. Levelized Cost of Electricity by Project and Weighted Average of Utility-Scale Solar PV systems by Region, 2014-2015. Reprinted from Renewable Power Generation Costs in 2015 (pg 27) by IRENA, 2016.

2.8. Models for the estimation of the PV systems costs

In order to implement a method that would help to predict the future tendency of the costs for Solar PV projects, a set of sources have been consulted. The main of them proposed a model to calculate the costs changes by evaluating the factors that influence into the cost reductions. (Kavlak, McNerney, & Trancik, 2018); (Taghizadeh-Hesary, Yoshino, & Inagaki, 2018). In there, a cost equation with different factors that might influence in the price (wafer area, module efficiency, yield…) was stated and implemented.

However, this was not what was desired for this study, since the aim was to use *Learning-by-doing* methodology. For that, the chosen model and the implemented one has been obtained from the report *Current and Future Cost of Photovoltaics by Fraunhofer, 2015* (Fraunhfoer ISE, 2015) where it is explained. Its principle is shown in *Figure 81.*

The model is based on an experience curve approach of the prices of that technology. This concept is based on the learning effects, which consider that prices on a specific product change (usually decrease) in some correlation when its production increases. Such model is mathematically expressed as:

$$C(x_t) = C(x_0) \cdot \left(\frac{x_t}{x_0}\right)^{-b} \quad (1)$$

With the accumulated production, x_t, and price $C(x_t)$ at some time t and the corresponding values for an arbitrary starting point x_0 and $C(x_0)$ and b as the learning parameter.

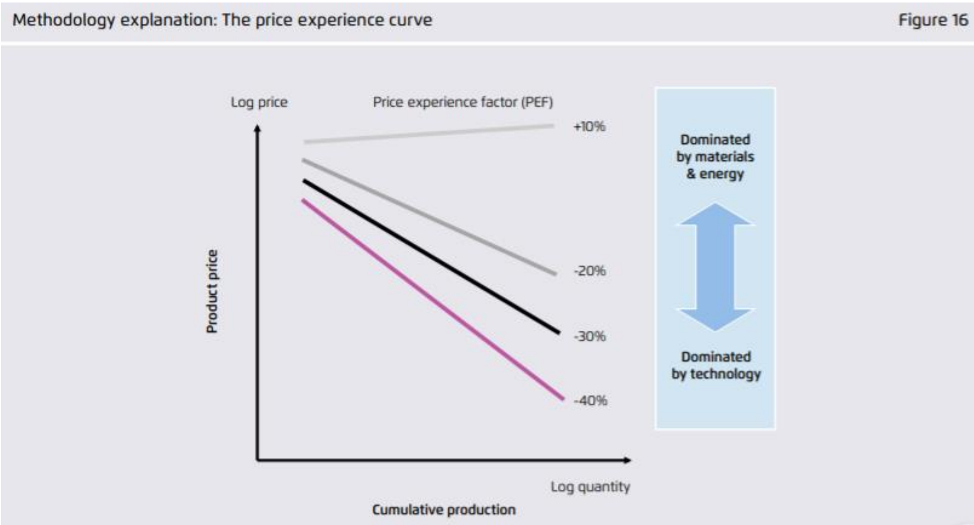


Figure 81. Methodology explanation: The price experience curve example. Reprinted from Current and Future Costs of Photovoltaics (pg 27) by Fraunhofer, 2015.

Applying the logarithmic function to the equation (1) it is possible to plot the linear experience curve to the price of the product and be able to make predictions of future prices by means of some linearity extrapolation. Moreover, it can be obtained the learning rate (LR) or progress ratio (PR) by means of the following equation:

$$LR = 1 - 2^b = 1 - PR \quad (2)$$

Such rate allows to understand how good the learning experience is affecting the prices of the product.

2.8.1. Prediction of residential PV systems costs in Australia by means of Learning Curves

In order to apply the Learning Curves methodology, it is required as much data as possible regarding the topic it is going to be evaluated; in this case, the costs of residential PV systems.

Thanks to *Solar Choice*, an Australian company, it was able to obtain a database of the costs of different capacity residential PV installations in Australia from 2012 until 2019. The evaluation of the costs by learning curve will be focused on the systems of 1,5 kW, 2 kW, 3 kW, 4 kW, 5 kW and 10 kW.

As said previously, to the data obtained from *Solar Choice* a 30% increase was applied in order to get the value without subsidy, since the given is with this discount applied. The study was conducted using these final values.

2.8.2. Methodology used for the prediction of the PV systems costs

Once it was plotted the trend of the real costs of the projects considered and specify the initial conditions x_0 and $C(x_0)$, it was possible to calculate the learning curve based on the data available and assuming a certain value of the parameter b. After having all the points from the learning curve by means of equation (1); after the $C(x_t)$ was calculated it was required to compare such curve -which was very dependent on the parameter b- with the real values and then, minimize (optimize) the error or difference by partial least squares by modifying the parameter b. (Fraunhfoer ISE, 2015)

Once the parameter b was calculated, the learning curve was defined and, following, in order to plot the future values, it was required to obtain the trend line that better describes the trend of the real costs, which is the logarithmic trend line. With the equation of such trend line, it was possible to obtain the future costs for the following years.

3. Sources of information: Databases for Solar Project Costs

Acceleration the technologic adoption requires the accessibility to low prices, and the competition is, usually, the best tool for that. In order to intensify the competition and obtain a decrease on market prices -especially for the less mature markets-, is important to have abundant, public and transparent information.

For that reason, several countries have invested important resources with the objective to develop project databases, where they are registered all the relevant components regarding prices and costs like the LCOE, the cost of total installation, the prices of the hardware technology, etc.

Following are presented the main sources of information currently available, where it is highlighted the ones from IRENA and NREL, thanks to its big and good deployment of information and graphics regarding the Solar PV sector.

- Lawrence Berkeley National Laboratory (LBNL) - information about registered solar pv systems in USA (https://emp.lbl.gov/tracking-the-sun/)
- National Renewable Energy Laboratory (NREL) - System Benchmark in USA (https://www.nrel.gov/lci/)
- International Renewable Energy Agency (IRENA) - LCOE evolution values (https://www.irena.org/costs/Charts/Solar-photovoltaic)
- International Energy Agency Photovoltaic Power System Programme (IEA PVPS) (https://www.iea.org/energyaccess/database/)
- REN21 - EU (http://www.ren21.net/)
- Fraunhofer - price evolution in Germany (https://www.ise.fraunhofer.de/en/renewable-energy-data.html)
- Solar Choice (website) - System prices for Australia (https://www.solarchoice.net.au/)
- PV Insight (website) - Module prices (http://pvinsights.com/indexUS.php)
- Energy Trend (website) - module prices (https://www.energytrend.com/pricequotes.html)
- Tracking the Sun (From LBNL) - Installation prices (https://emp.lbl.gov/sites/default/files/trackingthesun2018_data_public_4-oct-2018.zip)

- ENF Solar - Website containing prices for modules and inverters (https://es.enfsolar.com/)
- Australian PV institute (website) - Timeseries data per installation size (https://pv-map.apvi.org.au/postcode)
- IEA Auction Database: https://www.iea.org/

4. Results and discussion: The learning-by-doing and the Bright Future for the Residential Scale (in Australia)

By using the methodology explained in section *1.8) Models for the estimation of the PV system costs*, the analysis of the curves is done for each of the residential systems sizes with available and enough data. So, the analysis is done for 1.5 kW, 2 kW, 3 kW, 4 kW, 5 kW and 10 kW.

4.1. Learning curve and cost prediction for the 1,5 kW residential PV systems in Australia

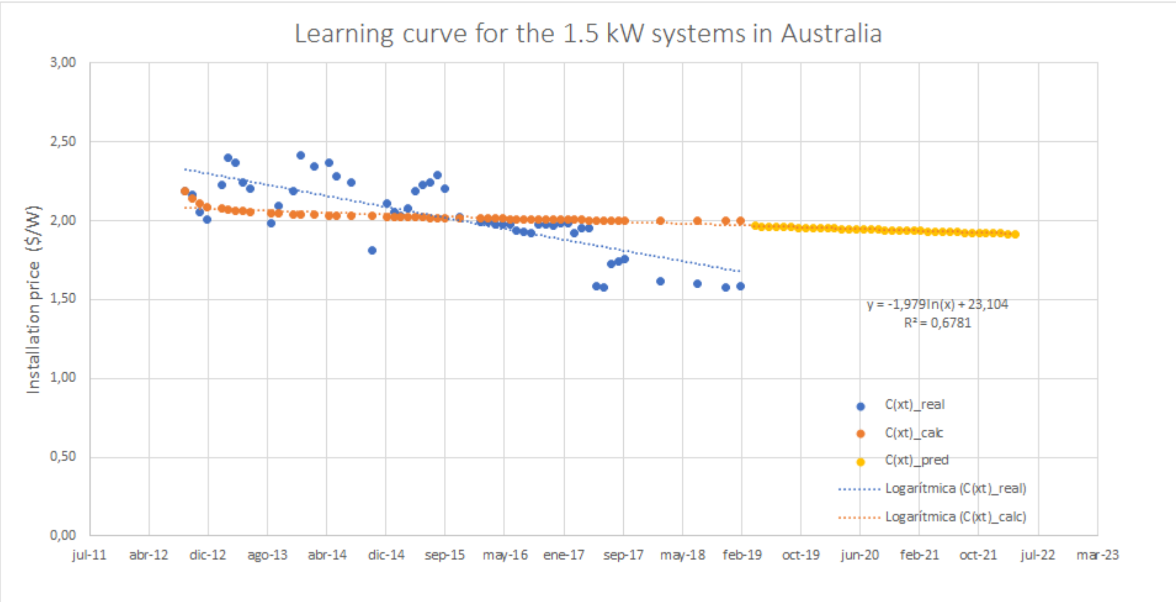


Figure 82. Learning curve for the 1.5 kW systems in Australia. Own creation based on data from Solar Choice, 2019.

The case of the 1.5 kW PV systems is a bit particular: as it can be observed in *Figure 82*, it presents a high variability in the first period, from 2012 to 2015, it can be observed a seasonal variability that is making prices increase and decrease even though that the general trend is to decrease.

For that reason, the usage of the learning curve method was difficult to apply with accuracy. With the objective to reduce such variability that was affecting directly the error with the learning curve, it was calculated the mean value at certain point t as the average of the 3 values before, the current value of time t, and the following 2 (a total of 6 points). This way, it was smothered the variability and with these average values it was recalculated the partial least squares, providing a better trend for the prediction.

Even though, as it can be observed in *Figure 83*, the trend that was obtained from the learning curve is no way close to the real trend as the prediction values seem to have a slow decrease meanwhile the real prices are decreasing in a more pronounced way.

4.2. Learning curve and cost prediction for the 2 kW residential PV systems in Australia

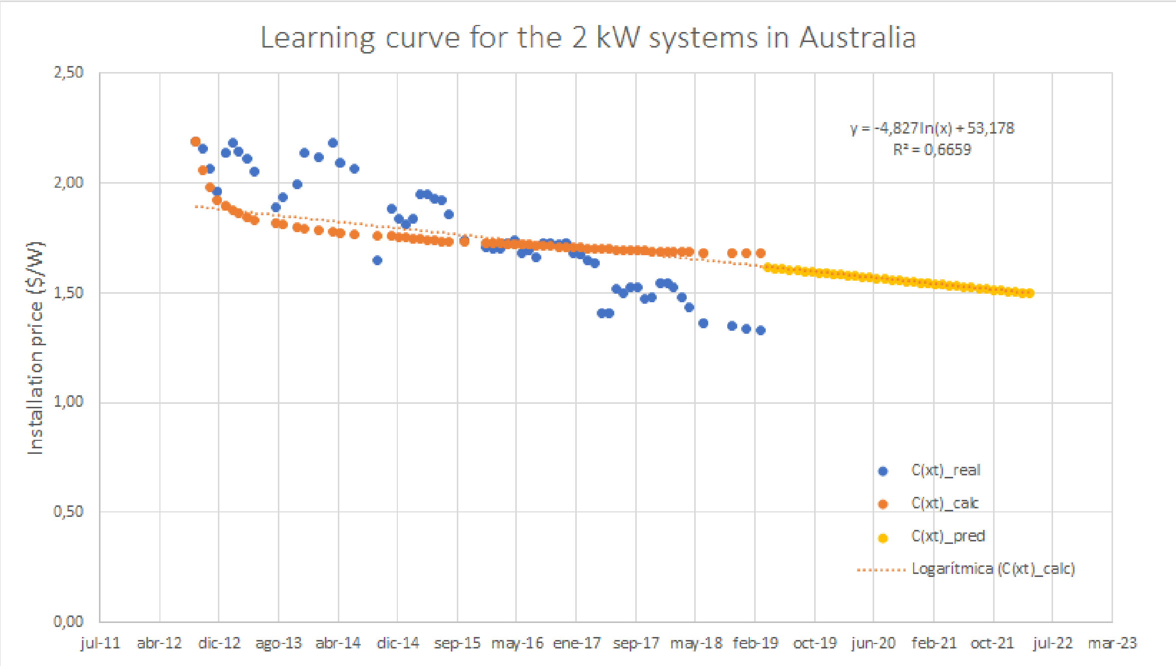


Figure 83. Learning curve for the 2 kW systems in Australia. Own creation based on data from Solar Choice, 2019.

Similarly, to the 1.5 kW systems, the 2 kW PV installations have some variability during the early periods of the data obtained and for that, it is also used the average values of the real costs to make such variability less relevant to the result.

As it can be observed in *Figure 83*, the final trend seem to follow a similar trend to the early real trend, however, at around 2018 real prices started decreasing in a steeper way, making look like the prediction trend is not close to the real values that should be expected and actually predicting more expensive prices, which are around 1.50 $/W for the 2022, than the real prices from February 2019, which are below the 1.40 $/W.

4.3. Learning curve and cost prediction for the 3 kW residential PV systems in Australia

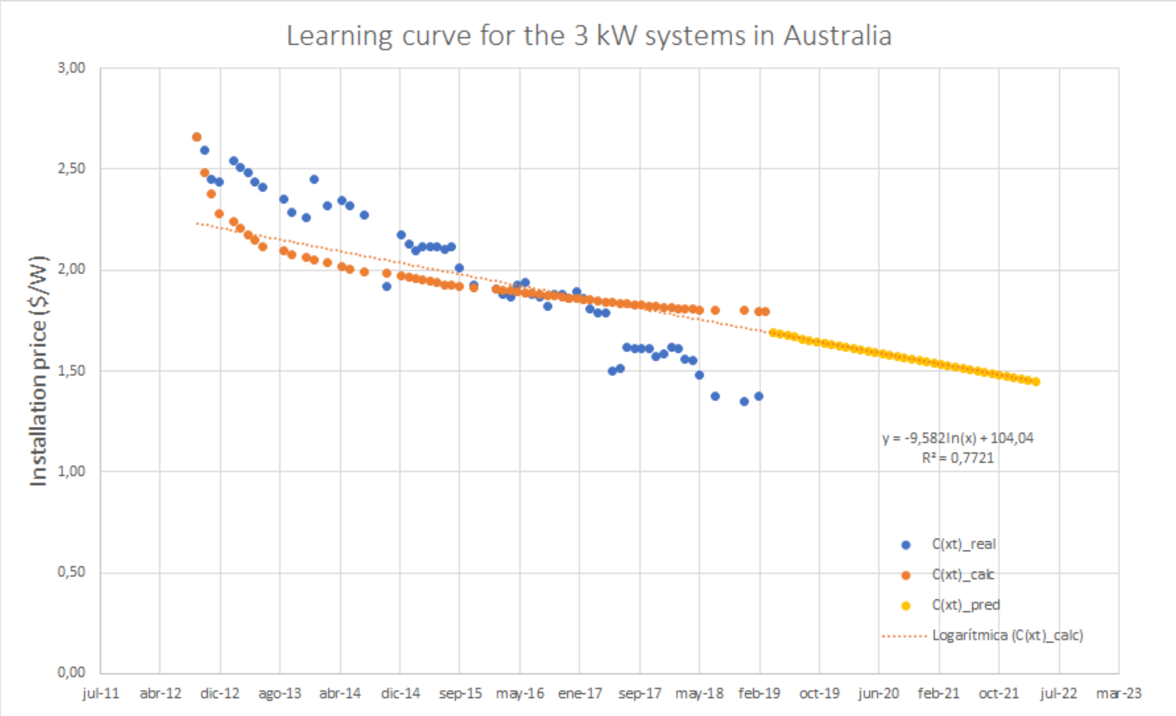


Figure 84. Learning curve for the 3 kW systems in Australia. Own creation based on data from Solar Choice, 2019.

The 3 kW solar PV installations in Australia, show a faster decrease of the costs, as *Figure 84* indicates, than the 1.5- and 2-kW systems and less variability in the early stages of the plot, making it possible to obtain a better trend prediction.

Looking at the prediction trend, in yellow, it seems like the cost evolution and its slope is quite like the real one but with a certain initial value error (February 2019) of about 0.40 $/W of differential. However, such learning curve, predicts prices of below 1.50 $/W for the 2022.

4.4. Learning curve and cost prediction for the 4 kW residential PV systems in Australia

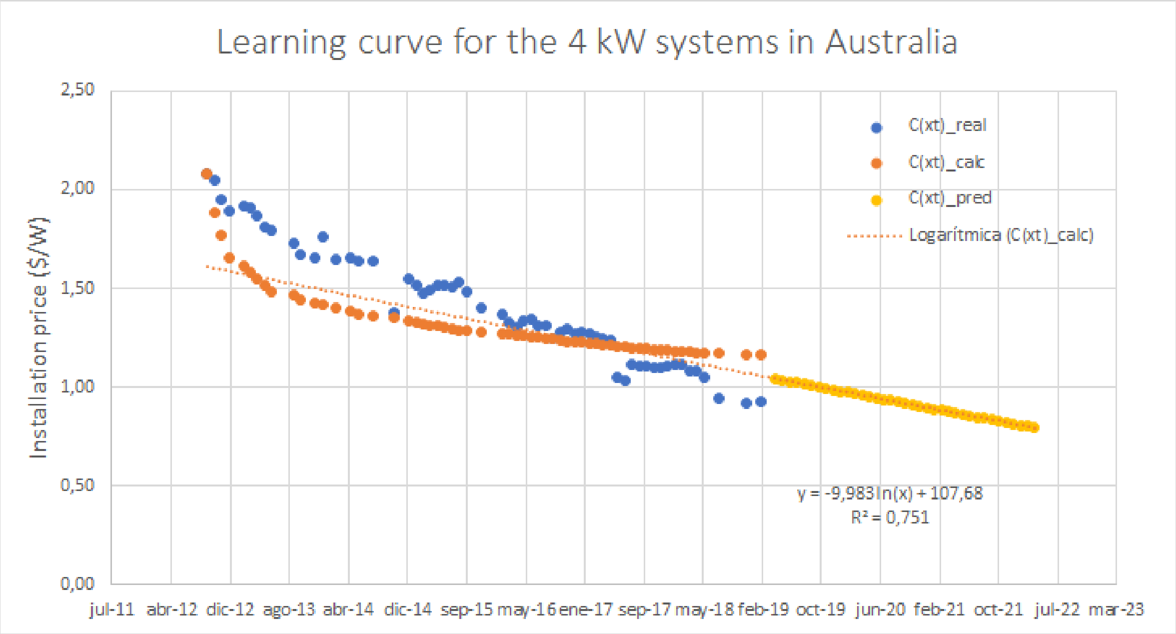


Figure 85. Learning curve for the 4 kW systems in Australia. Own creation based on data from Solar Choice, 2019.

For the 4 kW PV systems in Australia, it is found that their prices are following a more linear trend with a few variabilities. The fact that there is less variability than the other cases studied until now, makes the final learning curve prediction to be more accurate to the real values trend.

As it can be observed in *Figure 85*, the trend created seem to be very loyal to the real trend making it a trend to consider, predicting prices of 0.80 $/W for the 2022.

4.5. Learning curve and cost prediction for the 5 kW residential PV systems in Australia

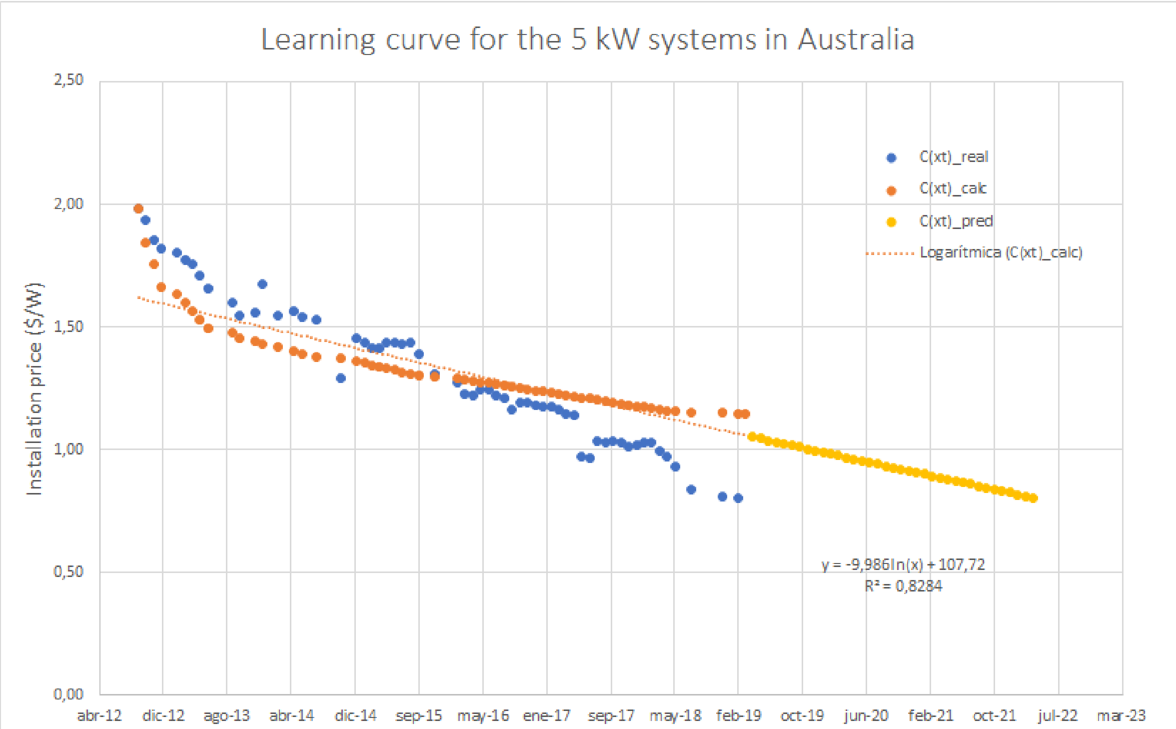


Figure 86. Learning curves for the 5 kW systems in Australia. Own creation based on data from Solar Choice, 2019.

The PV installations of 5 kW of capacity, as it can be seen in *Figure 86*, show also a rapid decrease in the prices. Such reduction in prices in the first stages in 2012, makes it a bit difficult for the learning curve to be as precise as it should be, also considering that the variability is quite low.

As a result of that rapid price decrease, the final prediction trend seems to be a bit far from the latest point of the real prices considered, which are close to the 0.90 $/W in February 2019. Even though, the trend seems to be fairly similar to the one for the real prices and it predicts prices close to the 0.80 $/W for the late 2021.

4.6. Learning curve and cost prediction for the 10 kW residential PV systems in Australia

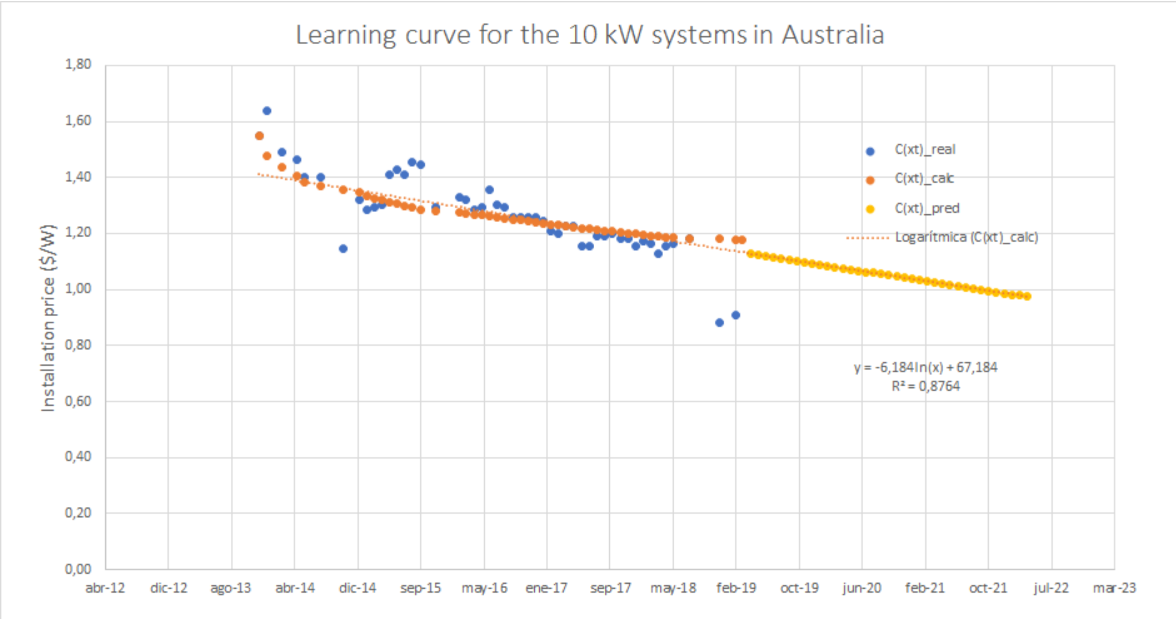


Figure 87. Learning curves for the 10 kW residential systems in Australia. Own creation based on data from Solar Choice, 2019.

The case of the 10 kW PV systems in Australia is quite particular due to the drastic reduction in prices that was experienced from 2017 to 2018. As it can be detected in *Figure 87*, the prices of the installations are kind of smooth until 2017 and such trend is also imitated by the prediction curve.

However, in 2018 prices started to reduce heavily and reaching prices around 0.90 $/W, making the prediction curve to be far from the real points, and, achieving higher prices close to 1.00 $/W for a later date (2021-2022) and making it to be not accurate as it seemed to be.

Conclusions

The first clear conclusion as for the costs in the solar PV projects, is that such technology has experienced a huge decrease in the recent years, mainly due to the increase on the projects and installations carried and the consequent improvement in the knowledge in this field which is also translated into improvement in the materials used, the efficiency of the manufacturing and installation processes, a concept that is also known by “Learning-by-doing”.

However, Solar PV is now reaching a certain point of maturity, since it is leading in numbers the new generation capacity additions, making such decrease to slow down. Hardware technology has been investigated and lots of improvements have been achieved thanks to the capital investment and Research and Development, making such technology difficult to improve and difficult to reduce more its prices.

That behavior affected the whole system costs, since hardware technology accounts for an important share of the total costs: about 35-40% in the smaller scales and around 50% for the utility-scale cases. For that reason, it has been recently spotted a bright opportunity to reduce the costs of solar PV in the non-hardware costs: the so-called Soft Costs.

Soft Cost account over a 50% in the small-scale systems, while in utility-scale they represent around 30%, making a bigger impact for the smaller cases. Such’s costs comprehend the taxes and Fees, the acquisition, transaction costs, the margin of profit, etc.

Moreover, it is also important to consider the Balance of System (BOS) costs, which usually compose around 20-30% of the costs including the installation of the BOS hardware

As it has been pointed, the influence of the scale of the system will affect notably the final costs of the system due to the scale economies, which allow to reduce costs -mainly of the hardware technology- thanks to the purchase of big quantities.

The final prices of each of the classified scales of systems clearly show this mentioned effect: for the residential systems it is estimated prices above the 2 $/W, for the commercial systems prices around the 1.5 $/W while for the biggest scale, the utility-scale, prices are around 1 $/W. Even though such prices data is the most recent available, it is also known that prices kept evolving until now and lower prices can obtain in the whole sector.

All these costs evolutions end up being reflected in the final cost of the energy, best represented by the LCOE. These prices, which allow easier comparisons with other technologies, are used as a reference to evaluate how is the Solar PV evolving: currently reaching prices between 30-40 $/MWh. However, such prices are better understood by supporting LCOE with, for example, the energy auction prices.

Regarding the leading countries and cheapest countries in the Solar PV sector, it has been found that China is one of the main producers of PV modules, together with Germany, both providing the lowest prices in the market. However, nowadays some other countries have evolved impressively with a cost reduction of installations around the 80% since 2010; this is the case of Italy, India and China, reaching prices of total installed systems below the 1 $/W.

Finally, thanks to some databases from Residential PV systems costs in Australia, it has been carried out a price prediction based on the learning curves method. From that, it has been concluded that, somehow, prices are difficult to predict when the variability of such prices are high, but when data is less variable it can be obtained an accurate learning curve. Thanks to the more accurate curves it has been estimated prices below the 1$/W in the residential systems between 3 and 10 kW. These results are very encouraging for the residential sector, allowing it to become more affordable for the families and, thus, make the transition towards a renewable economy possible.

Bibliography

References

[1] Anh Nguyen, P., Abbot, M., & Nguyen, T. L. (2019). The development and cost of renewable resources in Vietnam. *Utilities Policy*, 59-66.

[2] Ley Nº 20.257. Ministerio de Economía; Fomento y Reconstrucción. Santiago, 20 de marzo de 2008.

[3] Australian Government. (31 de May de 2018). *Australian Government - Clean Energy Regulator*. Obtenido de Small-scale Renewable Energy Scheme: http://www.cleanenergyregulator.gov.au/RET/About-the-Renewable-Energy-Target/How-the-scheme-works/Small-scale-Renewable-Energy-Scheme

[4] Bazilian, M., Onyeji, I., Liebreich, M., MacGill, I., Chase, J., Shah, J., . . . Zhengrong, S. (2013). Re-considering the economics of photovoltaic power. *Renewable Energy*, 329-338.

[5] BBC. (24 de January de 2018). *BBC News / World*. Obtenido de Estados Unidos: por qué Donald Trump impuso elevados aranceles a la importación de lavadoras y paneles solares (y cómo afecta ello a México y otros países): https://www.bbc.com/mundo/noticias-internacional-42798742

[6] Bijli Bachao. (2019). *Bijil Bacaho.* Obtenido de Solar Panel Price in India: https://www.bijlibachao.com/solar/solar-panel-cell-cost-price-list-in-india.html

[7] Branker, K., Pathak, M., & Pearce, J. (2011). A Review of Solar Photovoltaic Levelized Cost of Electricity. *Renewable & Sustainable Energy Reviews*, 4470-4482.

[8] College of Earth and Mineral Sciences, Pennsylvania State University. (2019). *Pennsylvania State University*. Obtenido de Mechanical BOS Components: https://www.e-education.psu.edu/ae868/node/914

[9] College of Earth and Mineral Sciences, Pennsylvania State University. (2019). *Pennsylvania State University*. Obtenido de Electrical BOS components: https://www.e-education.psu.edu/ae868/node/915

[10] Delony, J. (22 de January de 2018). *Renewable Energy World*. Obtenido de Trump Approves 30 Percent Tariff on Solar Panels Imports: https://www.renewableenergyworld.com/articles/2018/01/trump-approves-30-percent-tariff-on-solar-panel-imports-trade-industry-disappointed.html?cmpid=enl_rew_solar_energy_news_2018-01-23&pwhid=28d60bfd53749c356ad606db206b8233e2be5def404b132b773eac17a73a83c

[11] Dobrotkova, Z., Surana, K., & Audinet, P. (2018). The price of solar energy: Comparing competitive auctions for utility-scale solar PV in developing countries. *Energy Policy*, 133-148.

[12] Elliott, D. (14 de April de 2018). *Physics World*. Obtenido de Supporting renewables: FiTs not tenders?: https://physicsworld.com/a/supporting-renewables-fits-not-tenders/

[13] Energy Efficiency & Renewable Energy. (2019). *Energy Efficiency & Renewable Energy*. Obtenido de Soft Costs: https://www.energy.gov/eere/solar/soft-costs

[14] Energy Trend. (2019). *Energy Trend.* Obtenido de PV Spot Price: https://www.energytrend.com/solar-price.html

[15] Energypedia. (2014). *Energypedia*. Obtenido de Renewable Energy Tendering Schemes: https://energypedia.info/wiki/Renewable_Energy_Tendering_Schemes

[16] Energypedia. (2016). *Energypedia*. Obtenido de Renewable Energy Support Mechanisms: Feed-in Tariffs and Auctions: https://energypedia.info/wiki/Renewable_Energy_Support_Mechanisms:_Feed-In_Tariffs_and_Auctions

[17] ENF Solar. (2019). *ENF Solar.* Obtenido de Solar Panel Manufacturers: https://www.enfsolar.com/directory/panel

[18] EY. (2018). *EY.* Obtenido de Renewable Energy Country Attractiveness Index: https://www.ey.com/Publication/vwLUAssets/ey-recai-issue-51-may-2018/$FILE/ey-recai-51-may-2018.pdf

[19] Fang, L., Honghua, X., & Sicheng, W. (2016). *National Survey Report of PV Power Applications in China.*

[20] Fatimah, A. (29 de August de 2019). *ASEAN Centre for Energy*. Obtenido de Going Beyond LCOE: The real costs of variable renewable Energy: http://www.aseanenergy.org/blog/going-beyond-lcoe-the-real-costs-of-variable-renewable-energy/

[21] Fell, H.-J. (July de 2017). *Energy Watch Group (EWG).* Obtenido de The shift from feed-in-tariffs to tenders is hindering the transformation of the global energy supply to renewable energies : . http://energywatchgroup.org/wp-content/uploads/2018/01/FIT-Tender_Fell_PolicyPaper_EN_final.pdf

[22] Fowlie, M. (August de 7 de 2017). *Energy Institute At Haas*. Obtenido de The renewable Energy Auction Revolution: https://energyathaas.wordpress.com/2017/08/07/the-renewable-energy-auction-revolution/

[23] Frankfurt School - UNEP Centre/BNEF. (2018). *Global trends in renewable energy investment 2018.* Obtenido de http://www.fs-unep-centre.org

[24] Fraunhfoer ISE. (2015). *Current and Future Cost of Photovoltaics.*

[25] Fraunhofer ISE. (14 de March de 2019). *Photovoltaics Report.* Obtenido de https://www.ise.fraunhofer.de/en/publications/studies/photovoltaics-report.html

[26] Fu, R., Feldman, D., & Margolis, R. (November de 2018). *National Renewable Energy Laboratory.* Obtenido de US Solar Photovoltaics System Cost Benchmark: Q1 2018: https://www.nrel.gov/docs/fy19osti/72399.pdf

[27] Gürtürk, M. (2019). Economic feasibility of solar power plants based on PV module with levelized cost analysis. *Energy*, 866-878.

[28] IEA. (4 de February de 2019). *IEA*. Obtenido de Have the prices from competitive auctions become the "new normal" prices for renewables?: https://www.iea.org/newsroom/news/2019/february/have-the-prices-from-competitive-auctions-become-the-new-normal-prices-for-.html

[29] IEA PVPS. (2018). *Annual Report 2018.*

[30] IEA PVPS. (2018). *Trends 2018 in Photovoltaic Applications.*

[31] Industial Economics, Incorporated (IEc). (2017). *Solar Balance-of-System Costs Baseline Cost Study.*

[32] International Energy Agency (IEA) ; Nuclear Energy Agency (NEA). (2015). *Projected costs of Generating Electricity 2015 Edition.*

[33] IRENA. (2015). *Renewable Power Generation Costs in 2014.* International Renewable Energy Agency.

[34] IRENA. (2018). *Renewable Power Generation Costs in 2017.* Abu Dhabi: International Renewable Energy Agency.

[35] IRENA. (2019). *Renewable power generation costs 2018.*

[36] IRENA. (2019). *Renewable Power Generation Costs in 2018.* Abu Dhabi: International Renewable Energy.

[37] Jäger-Waldau, A. (2018). *PV Status Report 2018.* Luxembourg: Publications Office of the European Union.

[38] Kavlak, G., McNerney, J., & Trancik, J. (2018). Evaluating the causes of cost reduction in photovoltaic modules. *Energy Policy*, 700-710.

[39] Kost, C., Shammugam, S., Jülch, V., Nguyen, H.-T., & Schlegl, T. (2018). *Levelized Cost of Electricity. Renewable Energy Technologies.* Fraunhofer Institute For Solar Energy Systems ISE.

[40] Kruger, W., Eberhard, A., & Swartz, K. (2018). *Renewable Energy Auctions: A Global Overview.*

[41] LAZARD. (November de 2018). *Lazard's levelized cost of energy analysis - version 12.0.* Obtenido de https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf

[42] Long, R., Cui, W., & Li, Q. (2017). The Evolution and Effect Evaluation of Photovoltaics Industry Policy in China. *Sustainability*.

[43] Maeda, M., & Watts, D. (2019). The unnoticed impact of long-term cost information on wind farms' economic value in the USA. - A real option analysis. *Applied Energy*, 540-547.

[44] Motyka, M., Slaughter, A., & Amon, C. (13 de September de 2018). *Deloitte Insights.* Obtenido de Global renewable energy trends. Solar and wind move from mainstream to preferred: https://www2.deloitte.com/insights/us/en/industry/power-and-utilities/global-renewable-energy-trends.html?id=gx%3A2el%3A3dc%3A4direnenergy%3A5awa%3A6di%3A09132018

[45] PV Magazine. (May de 2019). *PV Magazine*. Obtenido de Module Price Index: https://www.pv-magazine.com/module-price-index/

[46] PVinsights. (2019). *PVinsights.* Obtenido de Index US: http://pvinsights.com/indexUS.php

[47] REN21. (2018). *REN21.* Obtenido de Renwables 2018: Global Status Report: http://www.ren21.net/gsr-2018/

[48] Ringbeck, S., & Sutterlueti, J. (2013). BoS costs: status and optimization to reach industrial grid parity. *Progress in Photovoltaics: Research and Applications*.

[49] SEIA. (2019). *Solar Energy Industries Association.* Obtenido de Solar Market Insight Report 2018 Year in Review: https://www.seia.org/research-resources/solar-market-insight-report-2018-year-review

[50] SEIA. (2019). *Solar Energy Industries Association*. Obtenido de Solar Industry Research Data. Solar Industry Growing at a Record pace: https://www.seia.org/solar-industry-research-data

[51] Solar Choice. (2019). *Solar Choice*. Obtenido de Solar System Prices Based on Live Data: https://www.solarchoice.net.au/blog/solar-power-system-prices

[52] Solar Choice. (12 de February de 2019). *Solar Choice*. Obtenido de Solar Power in Perth, WA: https://www.solarchoice.net.au/blog/solar-power-system-deals-perth-wa

[53] Taghizadeh-Hesary, F., Yoshino, N., & Inagaki, Y. (2018). *Empirical Analysis of factors influencing price of solar modules.* Tokyo: Asian Development Bank Institue.

[54] Thiéry, F. (09 de May de 2019). *Credendo*. Obtenido de Renewables: Enormous growth potential for wind and solar energy challenged by country-specific regulatory risks: https://www.credendo.com/news/renewables-enormous-growth-potential-wind-and-solar-energy-challenged-country-specific

[55] Tolouse School of Economics. (19 de September de 2018). *Toulouse School of Economics*. Obtenido de Learning by doing in the solar panel industry: https://www.tse-fr.eu/learning-doing-solar-panel-industry

[56] Wassbein, O., Glemarec, Y., Bayraktar, H., & Schmidt, T. (March de 2013). *Osti.Gov.* Obtenido de Derisking Renewable Energy Investment. A framework to support policymakets in selecting public instruments to promote renewable energy investments in developing countries: https://www.osti.gov/biblio/22090458

[57] Wikipedia. (March de 2019). *Wikipedia*. Obtenido de National Renewable Energy Laboratory: https://en.wikipedia.org/wiki/National_Renewable_Energy_Laboratory